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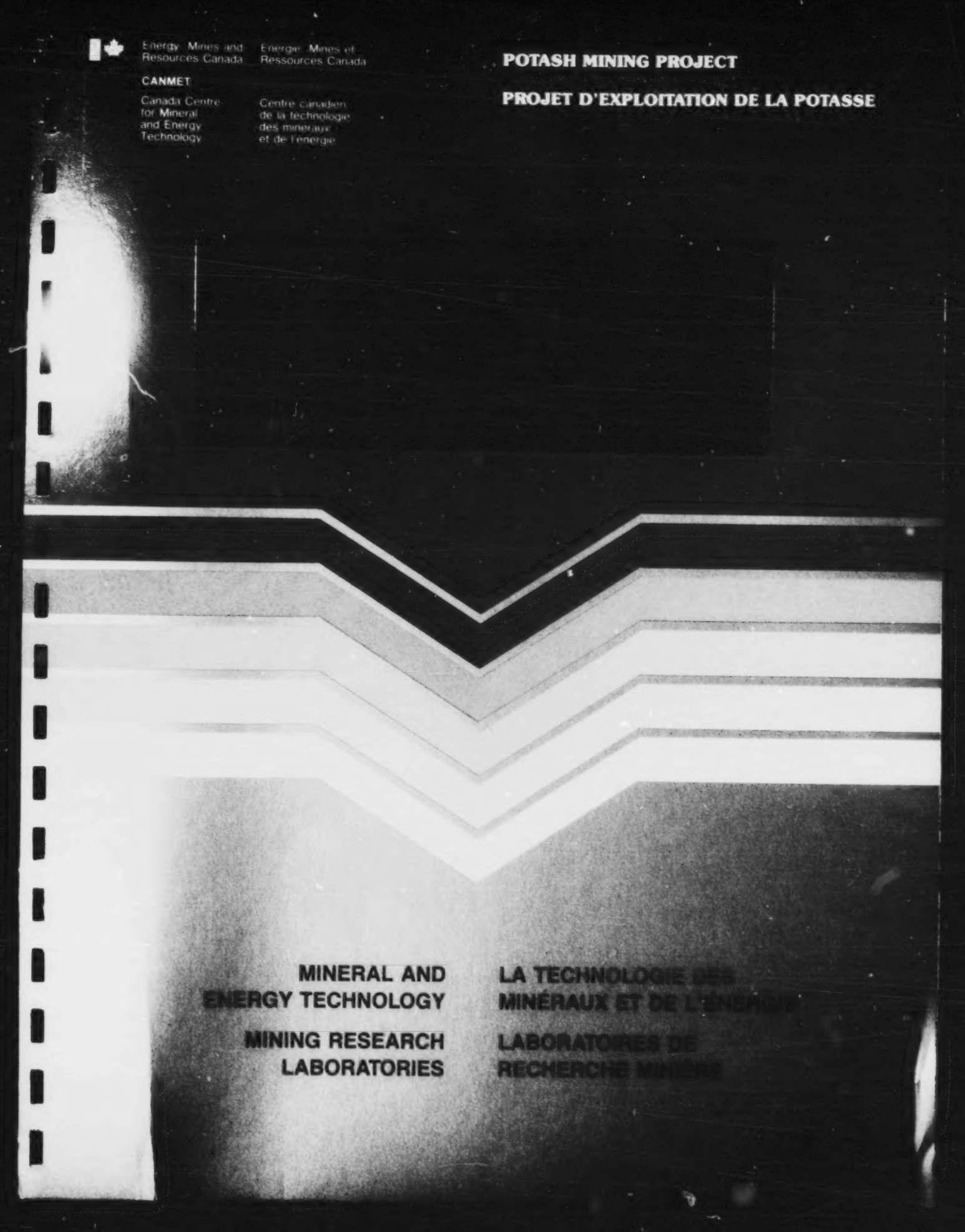
POTASH MINING PROJECT

PROJET D'EXPLOITATION DE LA POTASSE



MINERAL AND ENERGY TECHNOLOGY

MINING RESEARCH LABORATORIES

LA TECHNOLOGIE DES MINÉRAUX ET DE L'ÉNERGIE

LABORATOIRES DE RECHERCHE MINIÈRE

TITLE:

The Study and Predictive Modelling of Subsidence Induced by Potash Mining

Final Report
by
Potash Company of America
Division of Rio Algom Ltd.

July 13, 1990

Work on this project was conducted under the auspices of the Department of Energy, Mines and Resources

116 + fig.

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MICROMEDIA

ABSTRACT

Potash Company of America mines potash and rock salt from an evaporite structure to the east of Sussex in southern New Brunswick. Mining of the potash is by a continuous cut-and-fill method while the rock salt is mined using a room-and-pillar method. The mining operation is taking place under the Trans Canada Highway as well as the low lying Kennebecasis River valley. To precisely determine ground surface movements caused by the mining activity, a preliminary finite element analysis was carried out and a high quality geodetic monitoring network was established with the assistance of the Survey Engineering Department of the University of New Brunswick. Surveys of various types (vertical, horizontal, satellite Global Positioning System baselines and aerial photogrammetry) have been carried out over a two year period. This work will form the basis for a case history of surface subsidence induced by mining a complex evaporite body and will act as the first stage in the development of a predictive subsidence model.

RÉSUMÉ

La Potash Company of America extrait de la potasse et du sel gemme dans des dépôts évaporitiques situés à l'est de Sussex dans le sud du Nouveau-Brunswick. L'extraction de la potasse se fait selon la méthode déblai-remblai tandis que l'extraction du sel gemme utilise la méthode d'exploitation par chambres et piliers. L'exploitation minière est effectuée en-dessous de la route Transcanadienne ainsi qu'en-dessous de la partie inférieure de la vallée de la rivière Kennebecasis. Pour calculer avec précision les mouvements du sursol provoqués par l'exploitation minière, une analyse préliminaire des éléments finis a été effectuée et un excellent réseau de surveillance géodésique a été mis sur pied avec l'aide du département de génie de l'arpentage de l'Université du Nouveau-Brunswick. Des levés de plans de divers types (verticaux, horizontaux, levés avec le système de positionnement global par satellite, lignes de base et aérophotogrammétrie) ont été effectués sur une période de deux ans. Ces travaux constitueront la base d'une observation de cas de l'affaissement de la surface causé par l'exploitation minière d'une série évaporitique de minerai et serviront de première étape pour l'élaboration d'un système de prévision de l'affaissement.

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1.0 Introduction

Potash mining in New Brunswick presents challenges which differ significantly from those of mining other deposits in North America. The potash ore varies widely in both thickness and dip, dictating that mining must take place on different levels using a continuous cut-and-fill method not used in other potash mines. This results in the development of a unique composite of stopes in which almost 100% of the ore has been extracted.

High quality rock salt is also produced at the PCA operation. This is mined from the centre of the evaporite structure using a room-and-pillar method, with rooms typically 20 m wide, 20 m high and up to 300 m long. Part of the challenge which the Company must face is related to the geographical location of the ore body. Unique in New Brunswick and perhaps in Canada, the mining operation is taking place under the Trans Canada Highway with its associated ribbon development as well as the Village of Penobsquis. Running parallel to the highway, and within the region which would be affected by mining induced subsidence, is the flood plain of the Kennebecasis River system. This area is periodically water covered but is used by surrounding farms for cultivation during the summer.

Recognizing that the proposed surface subsidence study involved a substantial research component, the results of which could be of benefit to the mining industry The Canada Centre for Energy and Mineral Technology, CANMET, agreed to participate in its funding through the Department of Supply and Services. Funds were provided under the Canada-New Brunswick Mineral Development Agreement and the program was established in late 1988.

The purpose of the programme was to establish a high quality network of survey monuments which, in conjunction with remote monitoring techniques, would allow both vertical and horizontal movements to be detected. The survey monument network was designed and implemented with the assistance of the Survey Engineering Department, University of New Brunswick which is recognized for its leadership in the study of mining induced deformation. It is intended that the work should form the basis for a high quality case history of surface subsidence induced by mining. The initial involvement of the University of New Brunswick is seen as the first step in an ongoing cooperative project in which the data collected will be extensively used for both teaching and research purposes. This study, in conjunction with other geotechnical and mining data is anticipated to be used at a future date for the development of a predictive subsidence model.

2.0 Surface Subsidence Monitoring Network

The relationship of the present mining area to important surface features within the Kennebecasis Valley is shown in Figure 1 (in pocket). Using this information, together with geological cross sections of the area and known and assumed geomechanical rock properties, preliminary finite element modelling was carried out (Appendix A). This work allowed a surface subsidence survey network to be proposed. In practice the network had to be modified to deal with physiographic and social constraints existing in the field.

The existing road system allowed two approximately parallel survey lines to be established in a northeast-southwest direction. One line, along the Trans Canada Highway, is directly above the mine workings, while the other is across the river valley to the north. It was also possible to use secondary roads to establish parts of three lines running across the structure (A, C and E lines). Other lines were established along field or property boundaries and modified as necessary due to the low lying swampy areas in the Kennebecasis Valley between the two northeast-southwest lines. The low lying areas on either side of the axis of the evaporite structure are typical features of the development of salt pillows or anticlines. They are known as primary peripheral sinks and reflect the effect of salt migration at depth into the pillow. The trough on the south flank of the salt structure has been partially in-filled by Pleistocene deposition, while the north flank is occupied by the mature river system, leading to logistical problems in the establishment of an ideal survey network. In places the presence of housing and other structures also required some adjustment to the initially proposed survey lines.

A plan of the established network of survey monuments and their relationship to the mining area is shown in Figure 2. This relationship is shown in plan in Figures 3 and 4. The monuments themselves are 18 cm diameter steel reinforced concrete columns, 5 m deep. A few of the outlying monuments were established in bed rock but this was generally not possible in the valley where surficial sediments are typically over 30 m thick. In fact, some of the monuments are shorter than their design length due to the impossibility of maintaining a 5 m deep open hole in unconsolidated saturated sediments, while the concrete and rebar were being installed. Comparison of present and future survey data will help determine if such monuments are being effected by movements unrelated to regional mining induced subsidence.

Results

The results of the UNB survey campaigns are contained in Appendices A and B with the combined results of all the surveys to-date tabulated in Appendix E. These data are presented graphically in Appendix F, with Appendix G showing the calculated rate of subsidence for each of the survey monuments. As reported in the Preliminary Report by UNB on the 1990 survey (Appendix C), benchmarks along profiles C and D show statistically significant average subsidence of 9mm. However, meaningful interpretation of the results will only be possible if future surveys show that this trend is continuing.

Profiles have been constructed across the mining area (Fig. 5) and along the structure in the direction of mine development (Fig. 6) to help determine the location and amount of subsidence. Such profiling will be extended to cover all available section lines and will be updated as more information becomes available. This elevation data will also be shown in plan and contoured to demonstrate the location and magnitude of the subsidence trough. This will be used to determine the effectiveness of the original preliminary predictions of subsidence and will allow refinement of the modelling technique.

Photogrammetry carried out over the area in the course of this work is presently being digitized by Survey Engineering personnel, under a separate contract from PCA. It is anticipated that this will lead to the establishment of a high precision digital map which can be used as the basis for plotting, manipulating and interpreting future data.

Conclusions

A network of over 60 high quality subsidence monuments have been established over the existing mine workings, consisting of 5 north west - south east traverses across the area and 2 north east - south west longitudinal traverses. These monuments have been surveyed 4 times over a 2-year period indicating that minor, but statistically significant, subsidence does appear to be taking place. It has been predicted by preliminary finite element modelling that subsidence of 0.20m and horizontal displacement of 0.10m can be expected above the potash stopes. Subsidence above the extensive room and pillar salt mining area is anticipated to be somewhat greater, depending on the stope layout, which to-date has been determined by the structure of the deposit.

The object of this project was to establish a high quality subsidence network which would give reliable ground movement data, which could later be used to develop and refine a preliminary predictive model. This objective has been met. A secondary objective was that the project would establish a study area for such work for students, both undergraduates and graduates, and staff of the Survey Engineering Department of UNB. To-date, the University, through Dr. Adam Chrzanowski, have been involved in the design of the survey network, together with horizontal and vertical surveys, GPS surveys and preliminary photogrammetric interpretation. It is anticipated that the survey network will be expanded as mine development continues to the north east and that the close working relationship which has been developed between PCA and UNB will be strengthened with future surveys. Using data from these surveys together with those from other geotechnical work in which the company is involved will allow the refinement of the mine's predictive modelling capabilities of which this project was the preliminary step.

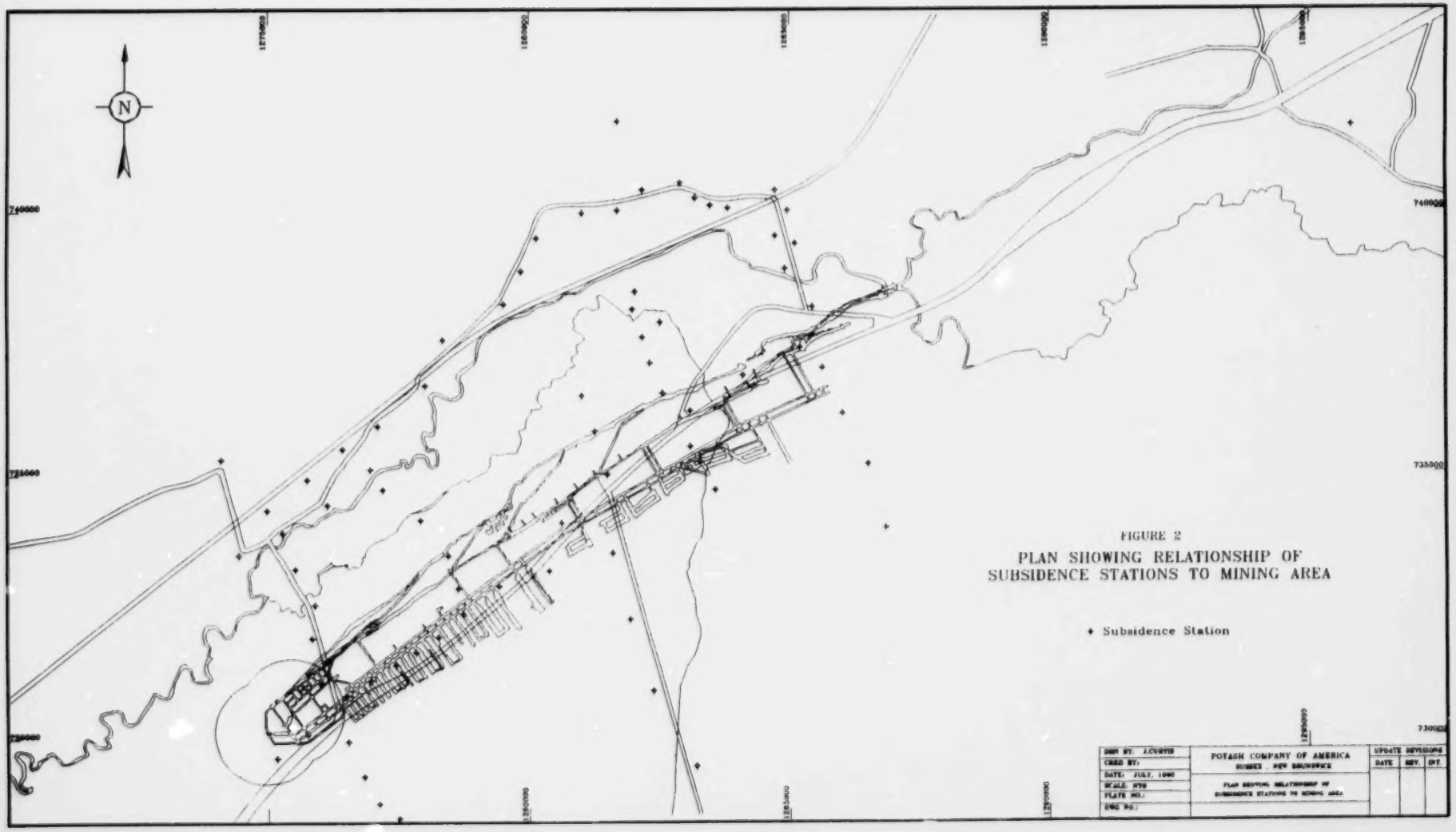


FIGURE 2

PLAN SHOWING RELATIONSHIP OF
SUBSIDENCE STATIONS TO MINING AREA

♦ Subsidence Station

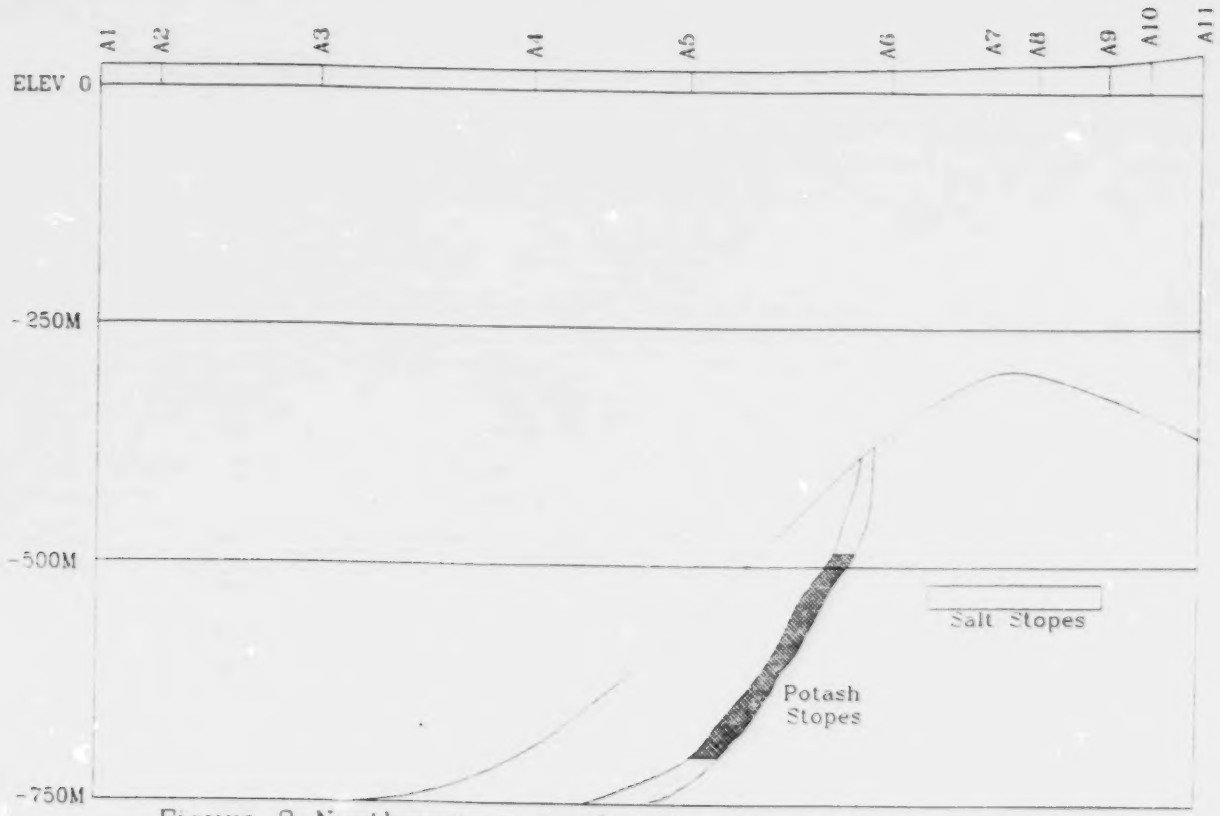


Figure 3 Northwest – southeast cross section of evaporite structure showing relationship of mine workings to top of salt and subsidence stations (line A)

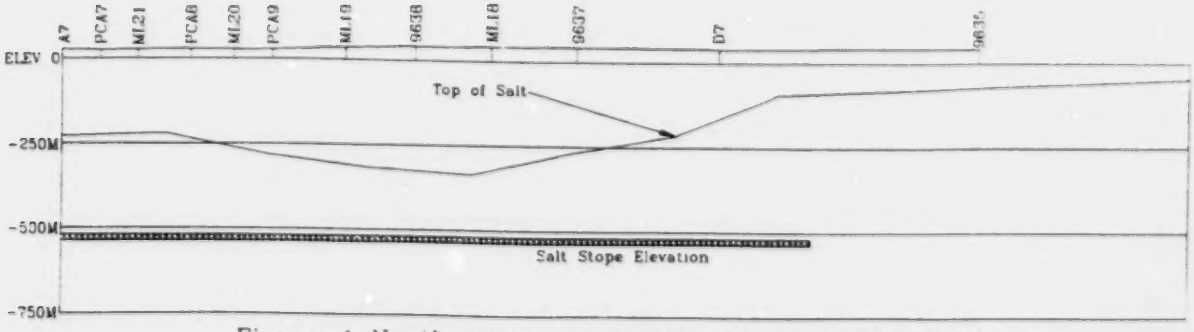
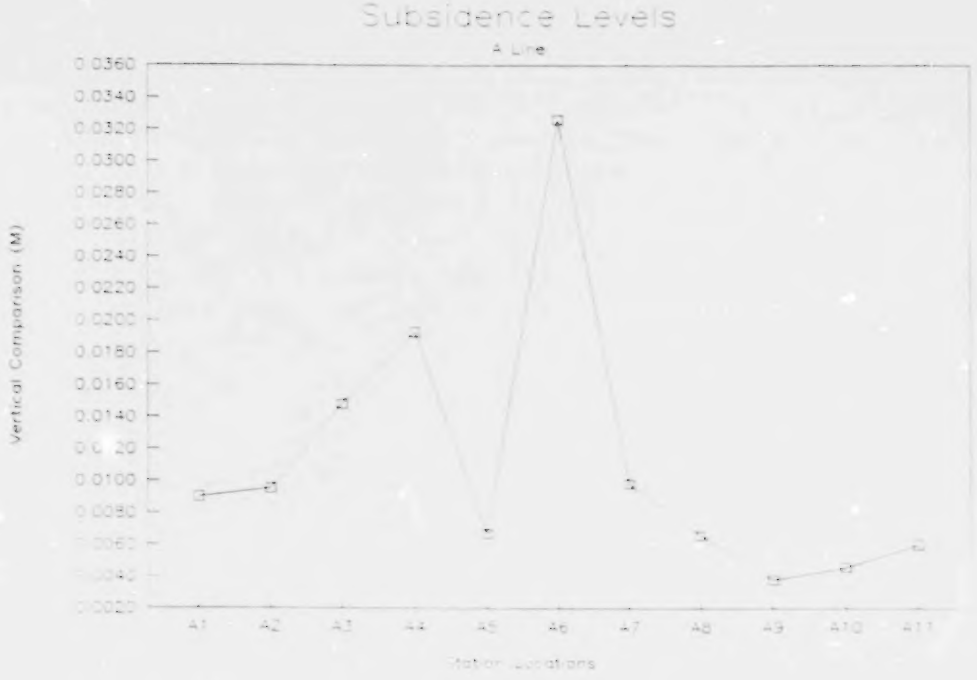
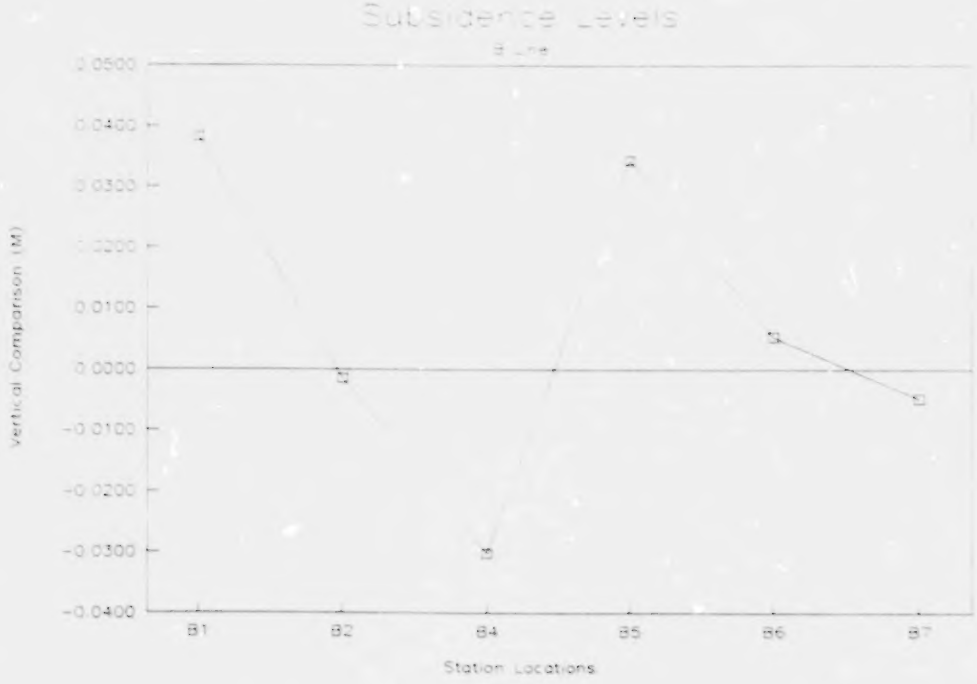
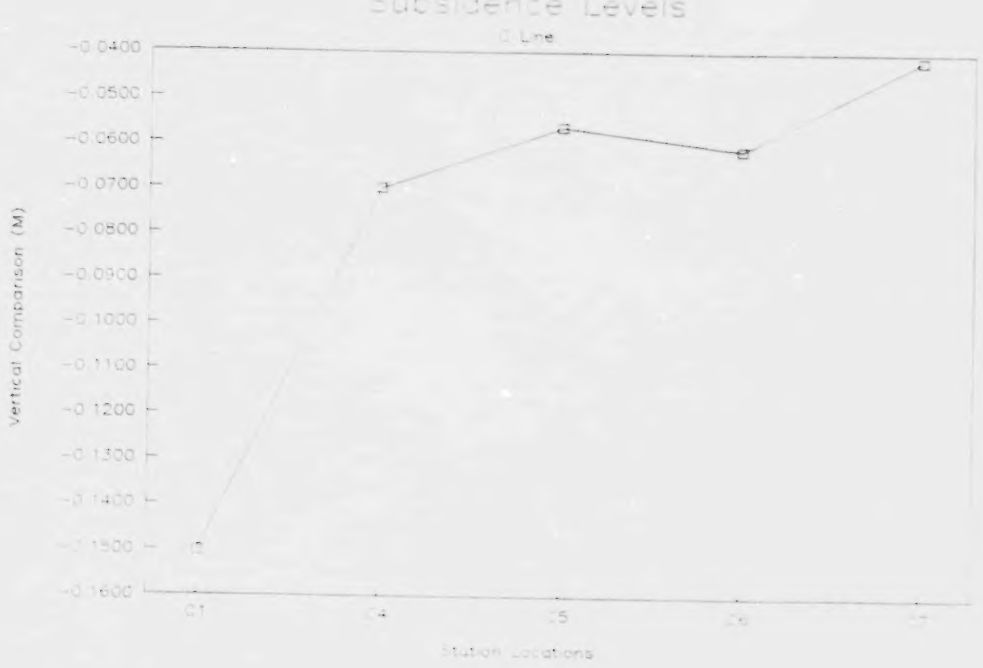
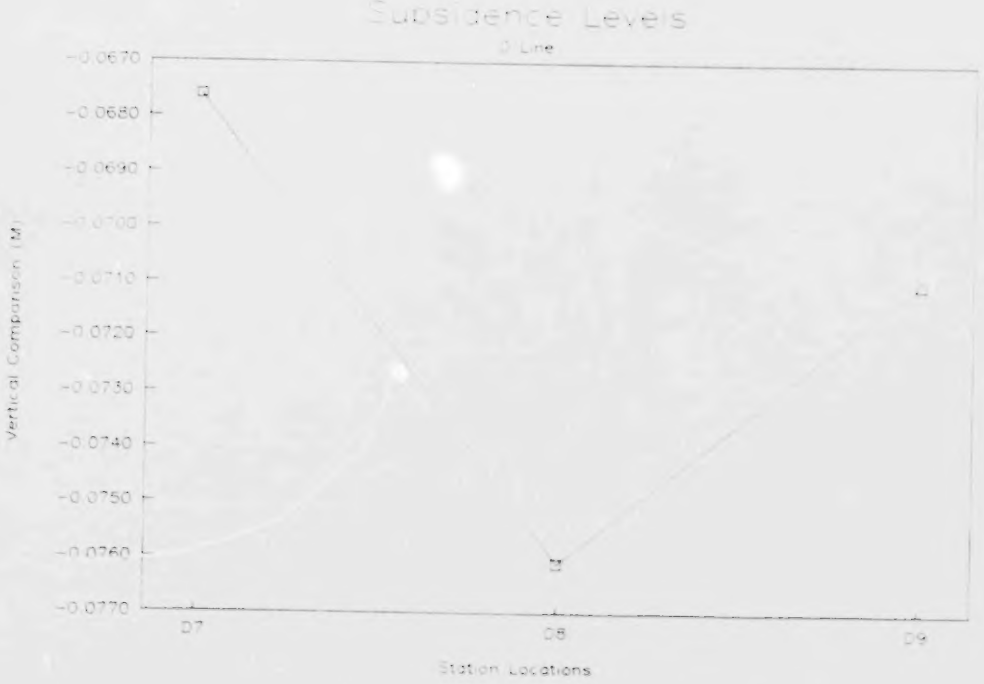


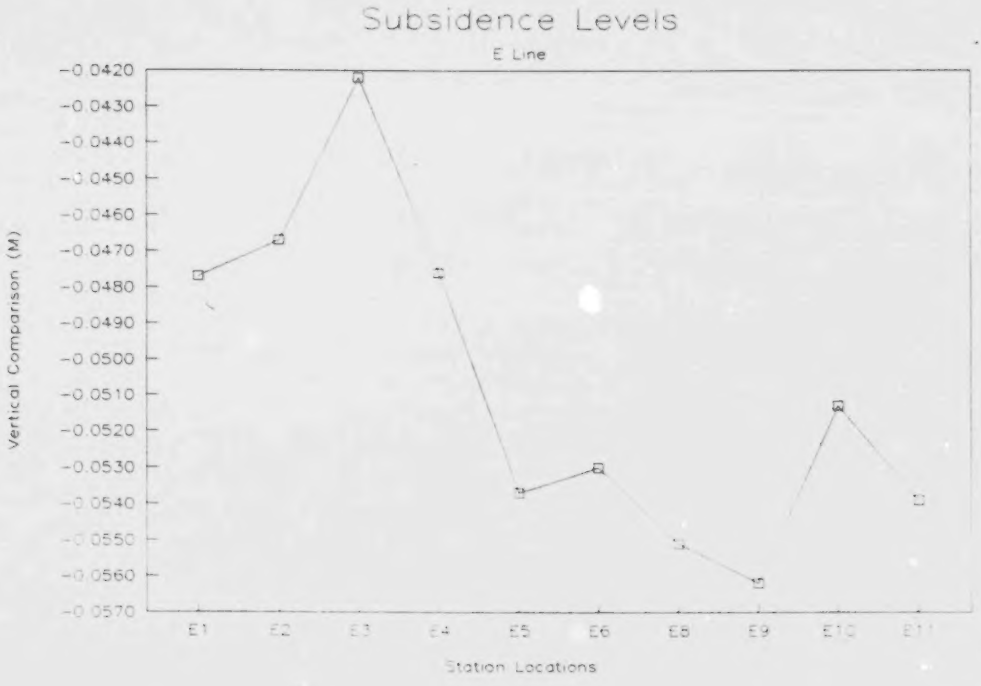
Figure 4 Northeast – southwest longitudinal section of evaporite structure underlying TCH subsidence stations

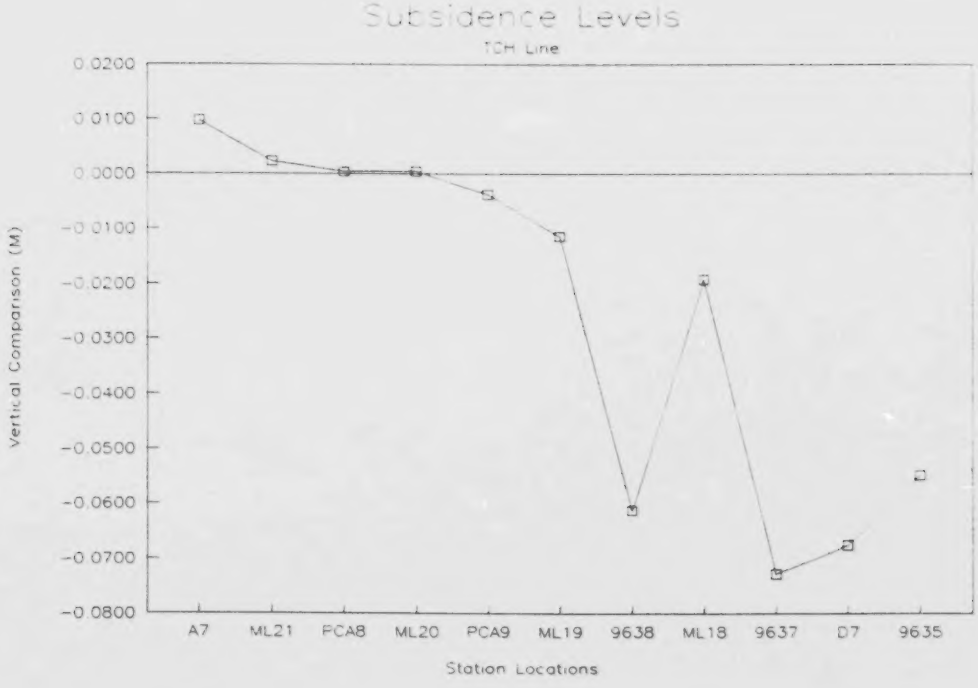

Subsidence Levels
A Line
Vertical Comparison (M)
0.0360
0.0340
0.0320
0.0300
0.0280
0.0260
0.0240
0.0220
0.0200
0.0180
0.0160
0.0140
0.0100
A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
Station Locations


Subsidence Levels
B Line
Vertical Comparison (M)
0.0500
0.0400
0.0300
0.0100
0.0000
-0.0100
-0.0200
-0.0300
-0.0400
B1
B2
B4
B5
B6
B7
Station Locations


Subsidence Levels
C Line
-0.0400
-0.0500
-0.0600
-0.0700
-0.0800
-0.0900
-0.1000
-0.1100
-0.1200
-0.1300
-0.1400
-0.1500
-0.1600
Vertical Comparison (M)
C1
C4
C5
C6
Station Locations


Subsidence Levels
D Line
-0.0670
-0.0680
-0.0690
-0.0700
-0.0710
-0.0720
-0.0730
-0.0740
-0.0750
-0.0760
-0.0770
Vertical Comparison (M)
D7
D8
D9
Station Locations


Subsidence Levels
E Line
-0.0420
-0.0430
-0.0440
-0.0450
-0.0460
-0.0470
-0.0480
-0.0490
-0.0500
-0.0510
-0.0520
-0.0530
-0.0540
-0.0550
-0.0560
-0.0570
Vertical Comparison (M)
E1
E2
E3
E4
E5
E6
E8
E9
E10
E11
Station Locations


Subsidence Levels
TCH Line
0.0200
0.0100
0.0000
-0.0100
-0.0200
-0.0300
-0.0400
-0.0500
-0.0600
-0.0700
-0.0800
Vertical Comparison (M)
A7
ML21
PCA8
ML20
PCA9
ML19
9638
ML18
9637
D7
9635
Station Locations

APPENDIX A

PRELIMINARY SCOPING ANALYSIS USING FEM

FINITE ELEMENT MODELLING OF GROUND SUBSIDENCE IN THE MINING AREA OF POTASH COMPANY OF AMERICA NEAR SUSSEX, N.B.

REPORT

submitted to Potash Company of America

by

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FINITE ELEMENT MODELLING OF GROUND SUBSIDENCE IN THE MINING AREA OF POTASH COMPANY OF AMERICA (PCA) NEAR SUSSEX, N.B.

1. Background Information

FEM Consultants in cooperation with the Department of Surveying Engineering at the University of New Brunswick (UNB) specialize in the modelling and analysis of ground subsidence in mining areas using the S-C Method. This method is based on an iterative non-linear elastic finite element analysis using the software FEMMA developed by FEM Consultants. A brief description of the S-C Method and FEMMA is given in Appendix I together with a few practical examples.

In the fall of 1988, Brian Roulston and his associates at PCA held discussions with Dr. Adam Chrzanowski and James Secord of UNB concerning the monitoring and analysis of ground subsidence in the area of potash and salt mining near Sussex, N.B. As a result, an agreement has been reached on establishing a geodetic monitoring network which would be measured by UNB in May 1989. In order to develop specifications for the monitoring surveys, information on the expected range of ground deformations in the subsidence area has had to be obtained first. Due to the complex geology of the mining deposits, lack of any previous subsidence measurements in similar conditions, and expected non-linear elastic and/or plastic behaviour of the strata, no empirical prediction method could be employed to give even approximate values for the deformations to be expected. Therefore, a decision was reached to use the services of FEM Consultants to employ the S-C method in predicting the subsidence.

On 29 December 1988, PCA issued a purchase order No.38006 to FEM Consultants to "perform finite element method analysis of area around mine site to determine extent and location of potential future subsidence caused by mining salt and potash".

This report summarizes the results of this analysis.

2. Available Input Data

The FEM analysis has been performed based on the following material supplied by PCA:

a) Two vertical cross-sections (1" = 40') of the mined potash deposit (Geological Sections 11250 and 15500) with pencil outlines of other geological strata and of mining workings in salt,

b) Topographic map 1 : 10000 with an outline of undergound workings,

c) Approximate geological cross-section of the whole area at an approximate scale of 1:40,000 (Fig. 1.)

d) Geomechanical properties of rocks which are summarized in Table 1.

A 30% volumetric closure in potash openings with dry stowing was given by PCA as an approximate estimation. No other parameter was available for the analysis.

3. Basic Concepts of the Analysis

It is generally accepted that the salt material, i.e. Basal, Middle, and Upper Halites, and potash in Fig.1 is characterized by viscous behaviour and creeping closure of openings. Given a long enough time, one may expect a complete closure of openings made in the material. Since the time related parameters within the salt dome have not been available, the FEM analysis has been made in a static mode after the complete closure of the openings (Fig.2) in salt and after the aforementioned 30% closure in potash.

Since the actual behaviour of the roof material in the salt dome has not yet been adequately determined, the propagation of influence of the openings towards the surface has been accepted as in a non-Newtonian liquid (flow of solids) assuming that the 'flown-in' material, after a long enough period of time, will create a cavity of the equivalent volume at the top of the dome (Fig.2). The influence of the equivalent cavity on the subsidence of the surface has been analysed following the S-C method described in Appendix 1.

4. FEM Analysis

Figure 3 shows the FEM mesh and the 'weak' zone determined above the equivalent opening. Two analyses have been performed:

1) analysis with the geomechanical properties of the rocks given by PCA and accepted as the in-situ properties and

2) analysis with the material properties treated as laboratory values, thus dividing the Young modulus by 3 (the standard procedure of the S-C method).

Both analyses were made as non-linear elastic with the iterative identification of anisotropic elements.

The second analysis seems to be more realistic because the given Young modulis have almost certainly been obtained from laboratory tests.

Appendix 2 gives listings of the input and output data of the second analysis. The results of the calculated subsidence and horizontal components of ground displacements are shown in Fig.4 and Fig.5 respectively.

5. Conclusions

The analysis indicates that maximum subsidence and maximum horizontal displacements in the potash mining area may reach values of about 0.20 m and 0.10 m respectively. Although the concept of the equivalent cavity should give a reasonably good approximation of the expected deformations, the analysis should be repeated when more information on the rheology of the material within the salt dome becomes available. Study on the creeping behaviour of salt is in progress and this capability will be included in the software of S-C method in a foreseiable future.

Anna Chrzanowski

Table 1. Geomechanical Properties of Rocks (as supplied by PCA)

Type of Rock	Young modulus MPa	Poisson ratio	Compr.strength MPa	Tens. strength MPa
1. Hopwell Group Siltstone & Sandstone	31000.0	0.18	100.0	5.0
2. Upper Halite Middle Halite Basal Halite	10000.0	0.35	19.0	0.8
3. Potash	5000.0	0.2	26.0	0.8
4. Upper Anhydrite	65000.0	0.35	50.0	5.0
5. Soln.collaps. Breccia	31000.0	0.35	-----	0.5

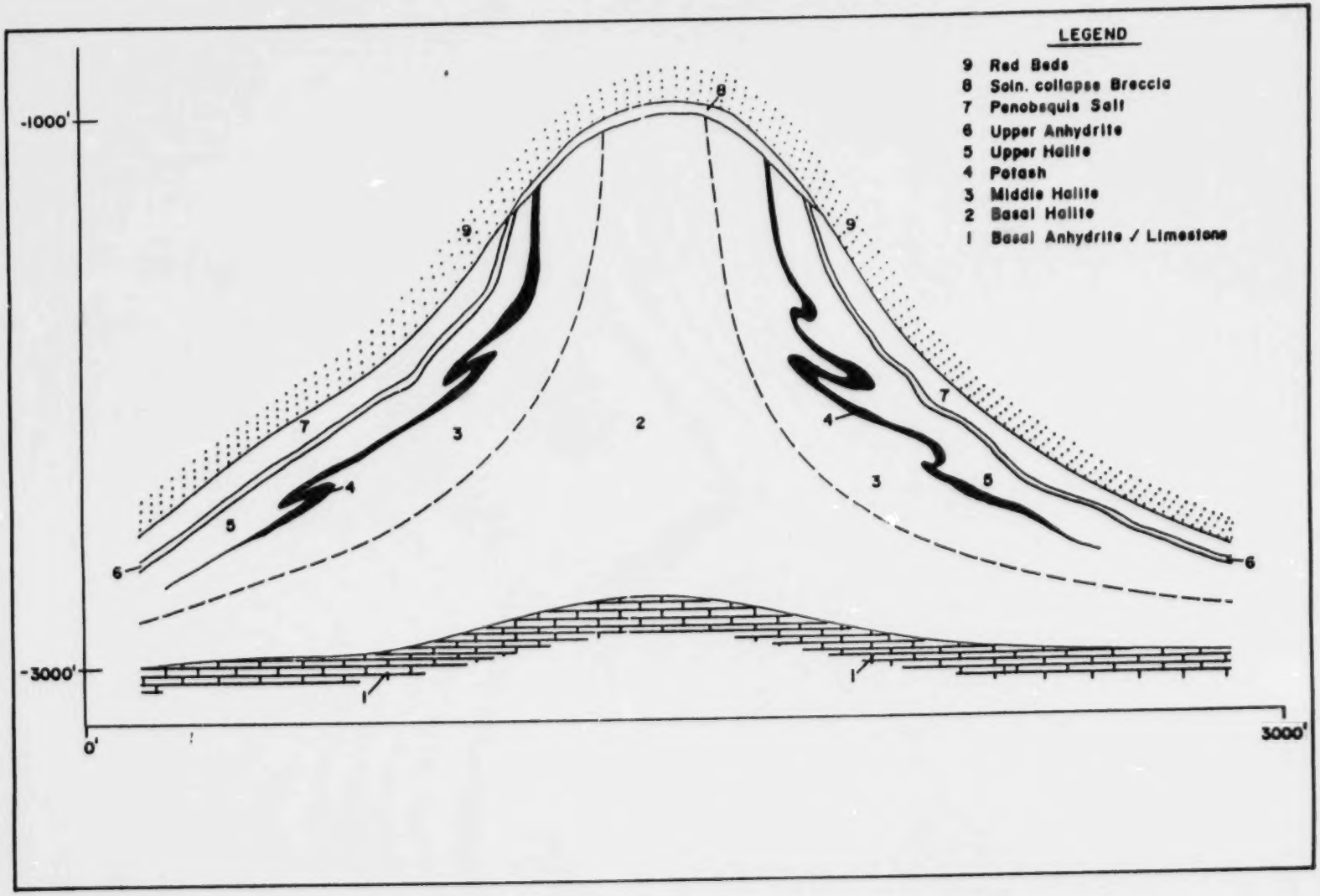

Figure 1. Schematic Geological Cross-section

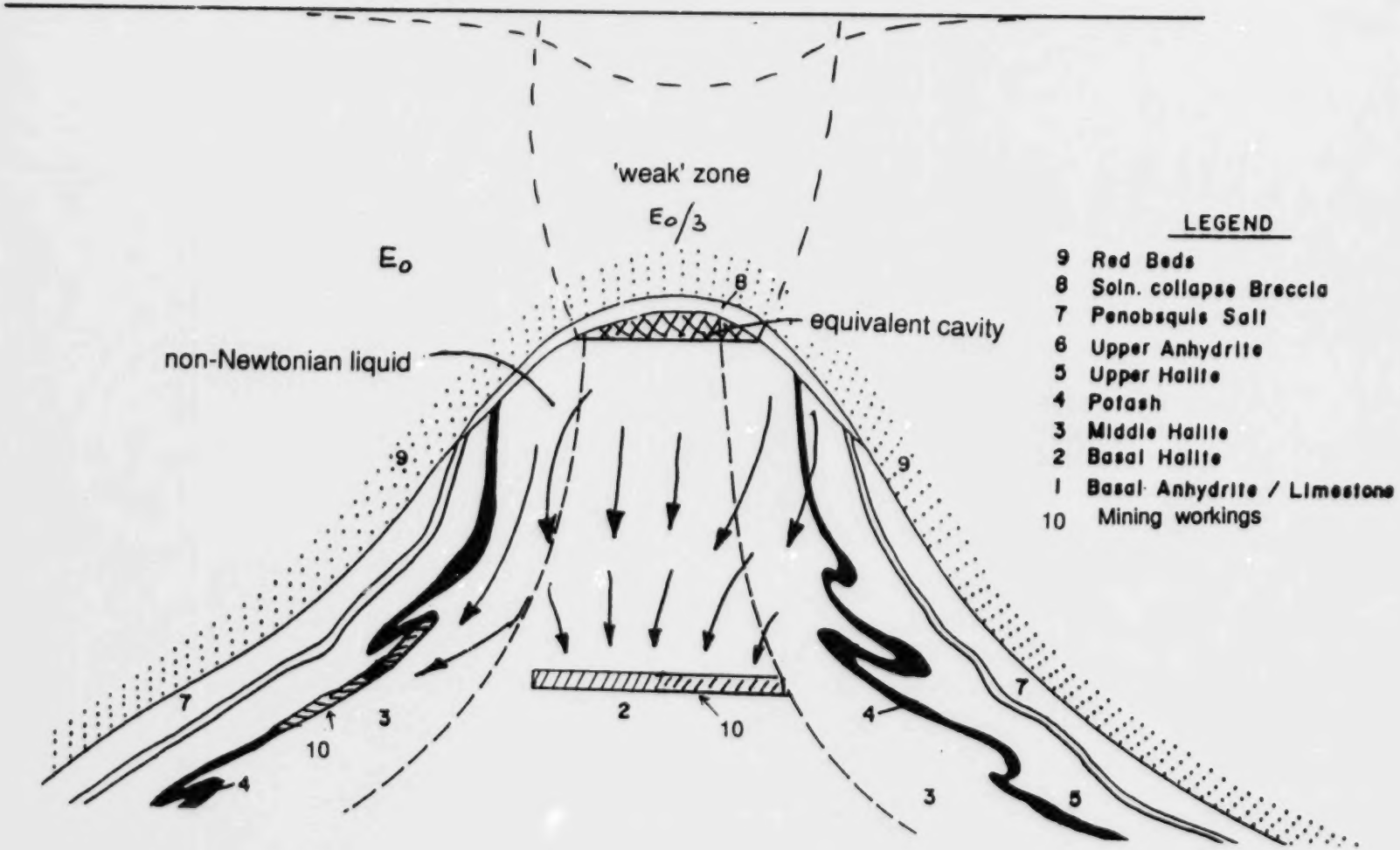

Fig.2. Qualitative Model of Subsidence Development

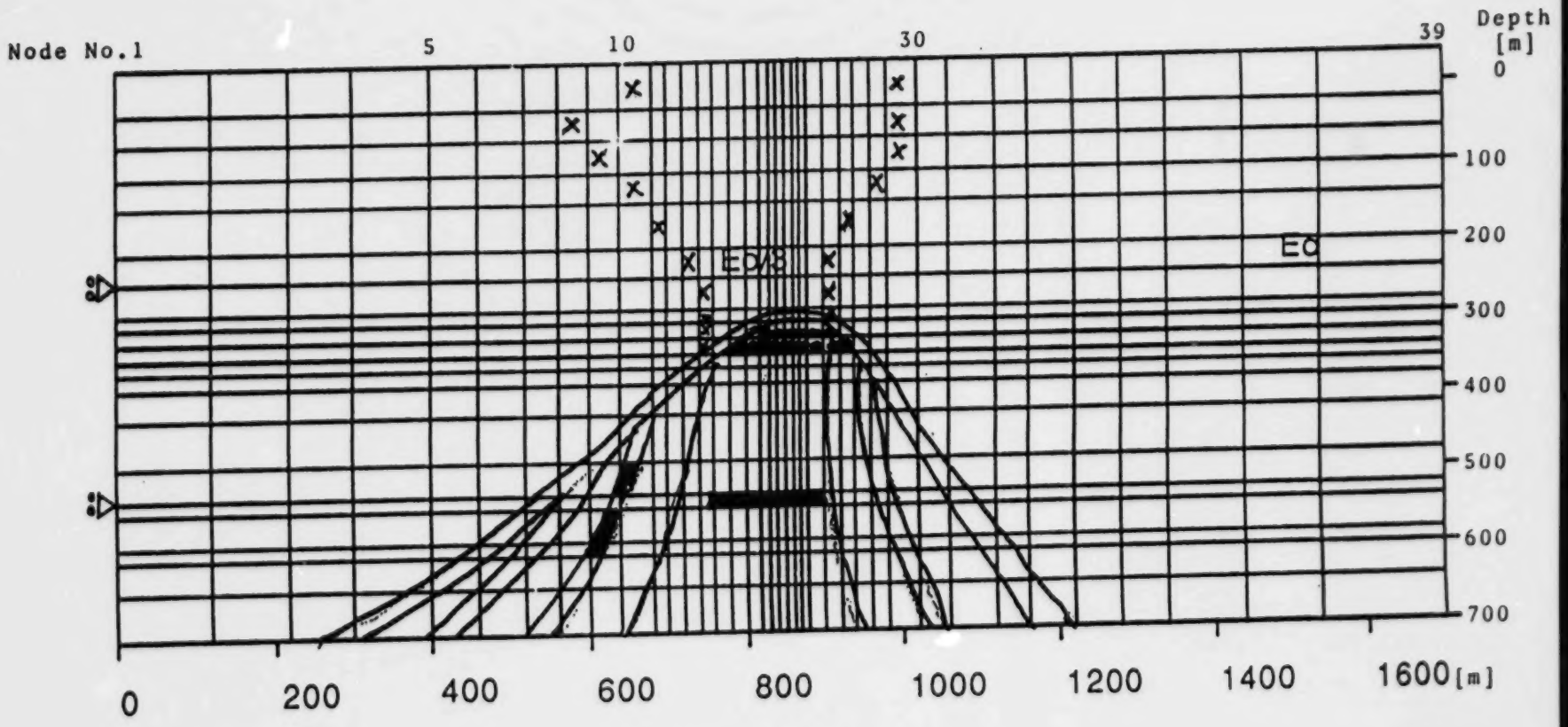

Figure 3. FEM Mesh

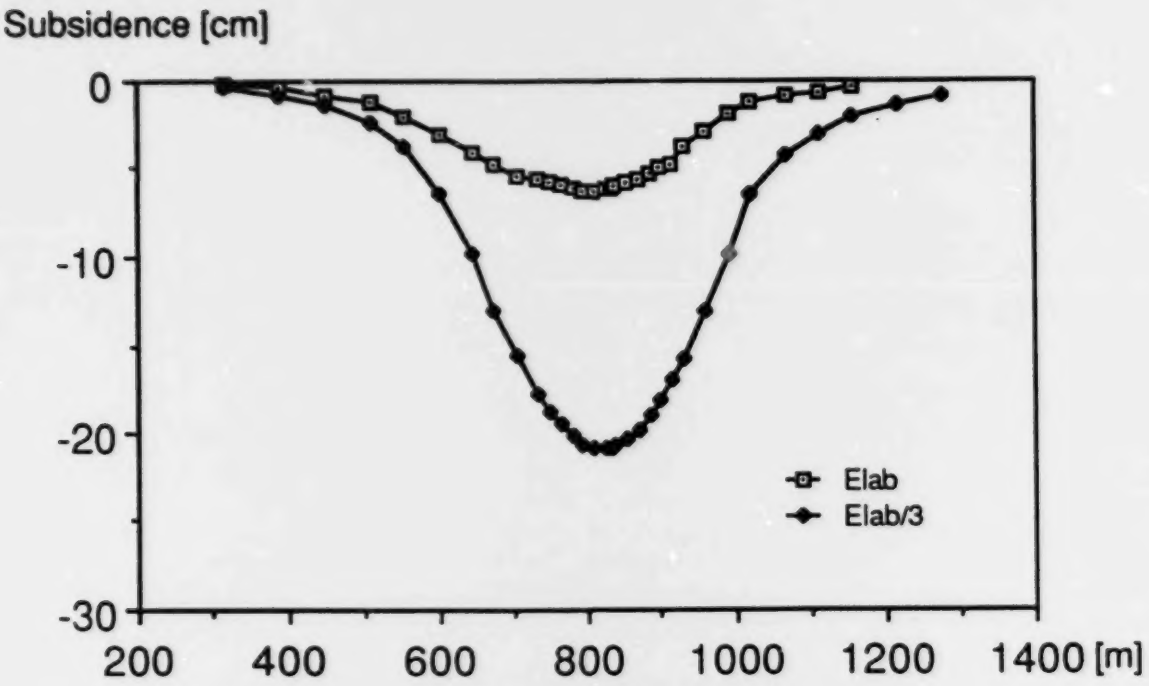

Figure 4. Subsidence Profiles

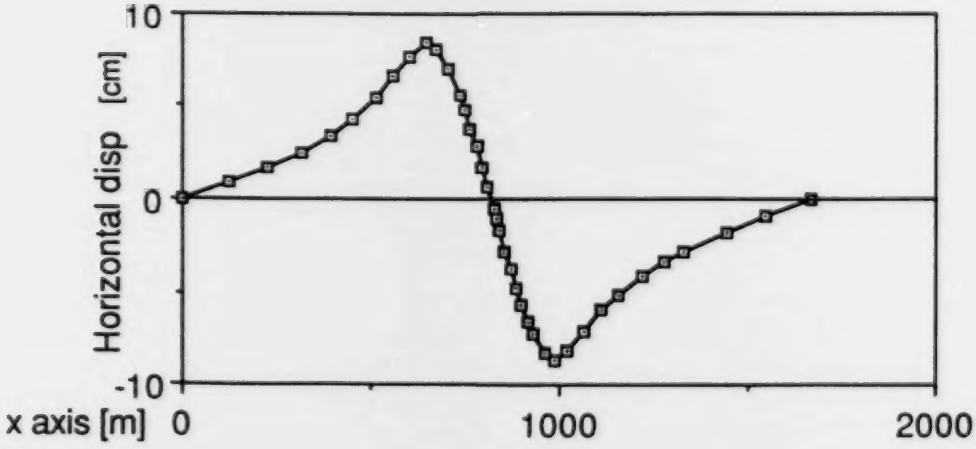

Figure 5. Horizontal Displacements

AN ITERATIVE MODELLING OF GROUND SUBSIDENCE USING NON-LINEAR ELASTIC FINITE ELEMENT ANALYSIS

Anna Szostak-Chrzanowski, M.Sc.E., Research Assistant, University of New Brunswick, Canada

ABSTRACT

A method, named the Szostak-Chrzanowski, or S-C, method, has been developed for modelling ground subsidence in mining areas. The method combines the general empirical knowledge on the behaviour of rock masses with the quantitative non-linear elastic finite element analysis. Software FEMMA, developed by the author, supports the S-C method, which has successfully been implemented in coal, lead and zinc, and copper mines.

INTRODUCTION

Ground subsidence may be described by one of the three models [Chrzanowski and Szostak-Chrzanowski, 1986]:

1. geometrical,
2. empirical (statistical),
3. deterministic (mechanistic).

• The geometrical model, through a geometrical analysis of monitoring surveys, describes the geometrical status of the deformed body, and describes the change of its shape and dimensions without any regard for causative effects and properties of the material.

• The empirical (statistical) model, through a regression analysis of the post-survey data and observed causative effects (loads), gives the load-deformation relationship which in turn may be used for predicting deformations as a function of known loads.

• The deterministic model, obtained from the a priori known properties of material, from mechanical relations between the loads (surface and body forces, initial stresses) and internal stresses, and from the physical laws governing the stress-strain relation, describes the expected deformation.

All three models complement each other. The geometrical model, which describes the actual deformations, helps not only in developing the empirical prediction models but also is used in enhancing ('calibrating') both the deterministic and empirical models through a comparison of predicted and observed deformations. On the other hand, quantitative understanding of the load-deformation relation obtained from the deterministic model helps in creating an empirical model and vice versa. In turn, both the empirical and deterministic prediction of the ground movements help in proper design of integrated monitoring surveys, selection of proper instrumentation, and their required accuracy and locations so that information can be optimally gathered on the actual deformation model. This general concept of the interaction between the integrated surveys, empirical and deterministic modelling of ground movements, and their statistical comparison is given in Chen and Chrzanowski [1986].

Most of the empirical theories for predicting subsidence have been developed in central Europe and the United Kingdom, where systematic and accurate monitoring surveys have been conducted in mining areas for several decades. The empirical models have been obtained through a correlation of the observed deformations with the causative effects which are usually expressed only in terms of the geometry and depth of the mined deposit and, in some theories, with qualitative information on

geology and the strength of rocks. Since other parameters, such as mechanical properties of the rock and tectonic stresses, are not taken into account, the prediction theories are applicable only to the areas where the mining, geologic, and tectonic conditions are the same or very similar to the area where the empirical data for the theory had been collected. Since the conditions in different areas are never the same, any attempt to adapt, for instance, the European empirical models for ground subsidence prediction on the North American continent requires the calibration of the model parameters through many years of comparisons with the observed deformations in the new area. Usually, this approach is unrealistic because very few, if any, mines in North America have a well organized and systematic program of monitoring surveys. It should be also stressed that the empirical theories are generally not reliable in cases of complicated geometry of mined deposits, in the presence of faulting, and in areas of previous extensive mining operations.

For the above reasons, the author in her research on the development of a prediction theory concentrated on the use of deterministic modelling of ground subsidence, rather than on adaptation of empirical models from other areas to North American conditions. The deterministic methods are definitely more universal than the empirical theories because they can be applied in any geological and mining conditions and they provide information not only on the surface subsidence but also on deformations within the rock masses and within the mining workings. However, the deterministic methods require reliable information on the in-situ properties of rocks, initial stresses, and tectonics of the area.

The in-situ properties of rocks are of a particular importance. They are difficult to be determined and they change in time according to the progress of the mining activity. It is the main reason that despite an intensive research performed at various research centres over the past several years, no successful method has been developed for predicting ground subsidence when using deterministic modelling alone.

The author in her search for the new method has combined the theory of deterministic modelling with the empirical knowledge and common sense related to the global behaviour (qualitative model) of rock masses above mining openings. The developed methodology, called the Szostak-Chrzanowski, or S-C, method, has been successfully tested in various geological and mining conditions and compared with actual subsidence profiles in coal, copper, and lead and zinc mines in Canada, the U.S.A., Poland, and the People's Republic of China. The method is based on an iterative non-linear elastic finite element analysis and is supported by software FEMMA (Finite Element Method for Mining Applications) developed by the author. A brief description of the method, illustrated with practical examples, follows.

SZOSTAK-CHRZANOWSKI (S-C) METHOD

Basic Concepts

In the S-C method, the in-situ rocks above the mining openings are treated as a non-linear elastic material in which the basic mechanical properties, particularly the Young modulus and the tensional strength, are changing with the progress of the mining exploitation.

Following Zienkiewicz et al. [1968], the method accepts (with limitations) the concept about the rock masses being a 'no-tension' material (zero tensional strength) particularly in the rock layers in the immediate roof of the mining opening. Generally in the S-C method, the tensional strength of the rocks is taken as varying from 1/40 of the compressive strength in the immediate roof to 1/10 near the surface.

Following Bieniawski [1984] and empirical findings of others, the in-situ values of the Young modulus of elasticity are taken as 3 to 5 times smaller than laboratory

values.

The most important concept of the S-C method is an introduction of the so-called 'weak' zone of rocks in the qualitative model of ground subsidence as shown in Figure 1. The weak zone is delineated by maximum shearing stresses which develop at the boundary between the zones of vertical tensional and compressive stresses produced by the mining opening. The boundary surface of the maximum shearing stresses had been identified by Kratzsch [1983] as a slippage surface of rocks which reduces transferring of the tensional stresses beyond the surface. In the S-C method, the limitation of the transfer of the tensional stresses is achieved by decreasing the Young modulus within the 'weak' zone by an empirical factor of 3.

Calculation Procedures using the S-C Method

Ground subsidence is a time dependant process. However, the S-C method has been basically developed for calculations of deformations in a static mode. The time dependency is introduced through an iterative process of calculations which follows these steps.

Step 1: Elastic solution without mining opening with given properties of the material (including anisotrophy) and with initial tectonic stresses if their influence is known. If in-situ elasticity parameters are unknown, then the laboratory values of E are reduced for the analysis by a factor of 3 to 5 depending on the qualitative properties of the rocks and using as guidelines some comparisons given by Bieniawski [1984].

Step 2: Elastic solution with the mining opening and determination of:

a) The 'weak' zone which is delineated by the elements with maximum shearing stresses between the opening and the surface. If obvious discontinuities (e.g., faults) are present in the vicinity of the opening, then the 'weak' zone is extended to the discontinuities;

b) critical tensional zone of the elements in which tensional stresses exceed critical values;

c) strains and displacements by combining step 1 and step 2 solutions.

Step 3: Repetition of Step 2 introducing:

a) E/3 in the 'weak' zone;

b) E=0 in the critical tensional zone (isotrophy) immediately above the opening (caving zone).

A new state of stresses and displacements is obtained and new elements with critical stresses may be obtained.

Step 4: Non-linear elastic solution introducing anisotrophy in the 'weak' zone by placing E = 0 in the direction of tensional stresses in all tensional elements obtained from Step 3. Additional boundary conditions are introduced for the vertical displacements (approximate maximum expected values) of the immediate roof points depending on the type of the backfill.

New state of stresses and strains is obtained with new tensional elements.

Step 5: Iterative repetition of Step 4 until no new tensional elements are obtained.

FINITE ELEMENT PROGRAMME 'FEMMA'

The computer programme FEMMA has been developed by the author for two-dimensional non-linear elastic analyses using quadrilateral four-nodal elements.

The programme is characterized by the following specifications:

- two-dimensional analysis of non-linear elastic deformations with options for either plain stress or plain strain cases;
- unlimited number of elements (the limit is given only by the capacity of the

computer);
- unlimited number of nodes, (limit is as above);
- unlimited number of material types (limited only by the number of elements);
- analysis with isotropic and anisotropic materials (the direction of anisotrophy does not have to coincide with the axes of the coordinate system);
- four nodal elements;
- application of four integration points;
- banded format of the total stiffness matrix what decreases the dimensions of the total stiffness matrix and therefore requires smaller memory of the computer.

The programme may utilize the following input data:
- initial stress,
- initial strain,
- body forces (as a unit weight),
- force boundary conditions,
- displacement boundary conditions,
- elasticity parameters (E and ν) for isotropic and anisotropic material,
- orientation of anisotrophy,
- strength parameters,
- choice of a criteria.

The output of the programme gives:
- displacement vectors at the nodal points, (x and y components, total displacement, and its direction),
- strain vector in each element,
- stress vector in each element,
- principal stresses and their orientation,
- list of elements in which the tensional stresses exceeded the given value,
- list of elements in which the compressive stresses exceed the critical values

The basic application of the programme is for elastic analyses. If tensional stresses are developed in the rock or when compressive stresses exceed given criteria, a non-linear analysis is performed by iterative solution of the time-dependent development of the subsidence which is caused by the mining exploitation.

EXAMPLES OF PRACTICAL APPLICATIONS

Shoemaker Coal Mine in West Virginia

The investigated mining operation is located at the Shoemaker Mine of the Consolidation Coal Company in northern West Virginia. The 1.7 m thick and 183 m wide coal panel is at an average depth of 180 m. The strata above the coal seam consists of limestone and shale (Figure 2.). The coal seam has been extracted using the long wall mining method with roof caving. Initial surface profile measurements were taken prior to the mining operation. The measurements were carried out during the extraction of the panel with the last measurement taken when ground subsidence reached its maximum value. The observed subsidence values have been given by Adamek and Jeran [1981]. The mechanical parameters of the rocks for this particular mine have not been published and they have been taken for the S-C analysis as average values published in Bieniawski [1984] and in Kidybinski, [1982] for the given types of rocks in similar geological conditions. The following mechanical parameters have been applied in the S-C method:
- average (in-situ) E = 16.2 GPa, the same for the whole cross section (divided by 3 in the 'weak' zone);
- Poisson ratio, ν = 0.14, the same for the whole cross section;
- average unit weight, $\gamma = 26$ KN/m^3;
- average compressive strength, $R_c = 70$ MPa, the same for the whole cross

section;

- tensile strength:
  - R_r = 1.70 MPa for the limestone in the immediate roof;
  - R_r = 3.50 MPa for the upper layers of limestone and for the shale below the top layer of limestone, and
  - R_r = 7 MPa for the surface shale.

Figure 3 shows the FEM mesh, boundary conditions, caved-in zone and anisotropic elements. The final solution has been obtained after 11 iterations. Figure 4 shows a comparison between the observed and calculated subsidence. The agreement is astonishingly good.

Coal Mine in People's Republic of China

The investigated mining operation is located on the central east coast in the People's Republic of China. Two side-by-side panels (Figure 5) of an inclined (11°) and 4.2 m thick coal seam have been extracted at an average depth of 150 m using the long wall mining method with roof caving. The geological strata (Figure 6) consisted mainly of sandstone and shale. The exploitation of the two panels took place in 1966. Subsidence measurements had commenced prior to the exploitation and ended in 1968. The finite element analysis using the S-C method was performed along the A-A cross section which coincides with the geodetic line (Figure 5). The mechanical parameters were not available to the author. Therefore, average values (Table 1) have been accepted as published in Kidybinski [1982] for the same types of rocks in coal mines in Poland. Figures 7 and 8 show the FEM mesh and the comparison of the subsidence results, respectively. The agreement is very good.

Table 1. Properties of rocks; coal mine in East China

Material	R_c [MPa]	R_r [MPa]	E [GPa]	ν	γ [kN/m]
Sandstone	60.0	1.2	11.0	0.20	26.0
Shale	40.0	2.8	12.2	0.20	26.0
Shale + soil	10.0	2.9	3.0	0.30	26.0
Coal	20.0	0.8	3.5	0.25	13.0

LEAD AND ZINC MINE IN SOUTHERN POLAND

The investigated lead and zinc mine is located in Upper Silesia in Southern Poland. A two-level extraction of an ore bearing dolomite with a thickness of 4 m and 5 m of the lower and upper panels, respectively, at a depth of about 200 m, was separated by a 4 m thick unexcavated layer. Figure 9 shows a schematic geological cross section. Table 2 shows geotechnical data of the rocks as published by Kidybinski [1982] for the given mining area.

Table 2. Lead and zinc mine; mechanical properties of rocks.

Material (see Fig. 9)	R_c [MPa]	R_r [MPa]	E [GPa]	ν	γ kN/m
No. 1	29.0	2.1	6.0	0.40	21.0
Ore dolomite	80.0	2.0	18.0	0.15	21.0
No. 2	64.0	3.0	19.0	0.20	21.0
Jurassic	50.0	4.0	8.0	0.20	21.0
No. 3	57.5	3.0	16.0	0.15	21.0
Backfill	29.0	2.1	0.12	0.40	21.0

The mining of the ore began in 1973 and ended in 1981. A hydraulic backfill was used in both excavated panels with an estimated 15% consolidation. The Young modulus of the hydraulic backfill (sand) was assumed equal to 120 MPa. Measurements of the surface movements started before the mining operation and ended when the surface movements stopped.

The finite element model is shown in Figure 10. In the analysis, the 'weak' zone has been extended to a fault zone (Figure 10) which was marked on mining maps. Figure 11 shows a comparison between the measured and calculated subsidence.

CONCLUSIONS

The developed method for deterministic modelling of ground subsidence provides a universal tool for predicting purposes in any geological and mining conditions. The presented examples show excellent agreement between the calculated and observed deformations, though the data on the geomechanical properties of the rocks had to be approximated from publications related to other mines or even other mining regions. The program FEMMA, in its present form, is applicable only to a two-dimensional analysis along cross sections of elongated shapes of excavations. Its adaptation to three-dimensional analysis is in progress. The reader is referred to Chrzanowski and Szostak-Chrzanowski [1987] for additional examples of the application of the S-C method.

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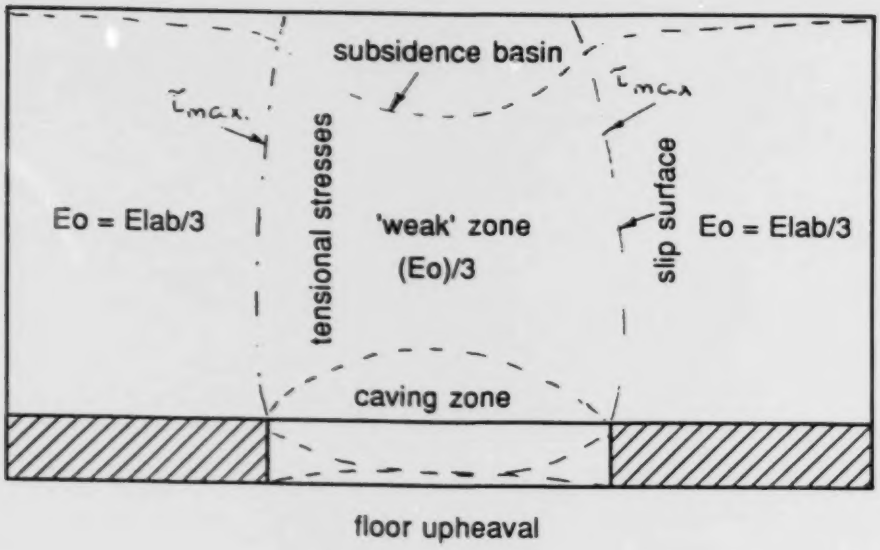

Figure 1. Basic Qualitative Model of Ground Subsidence

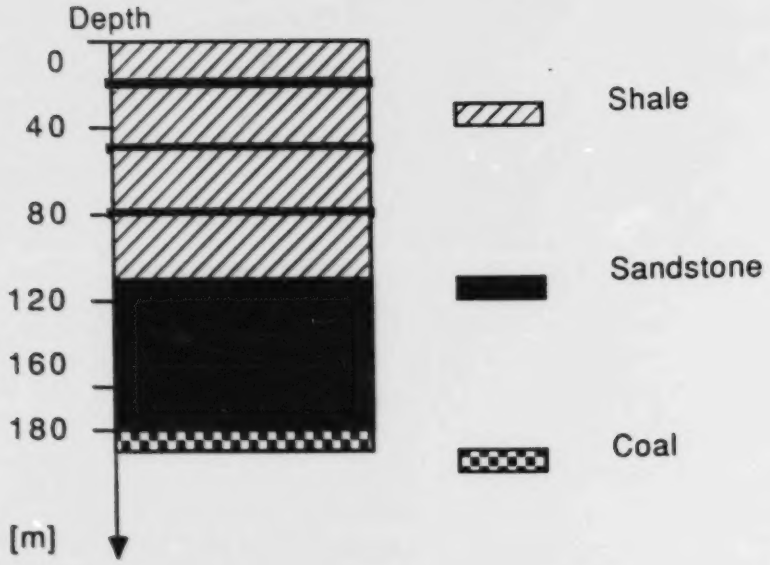

Figure 2. Geological Profile - Shoemaker Coal Mine (USA)

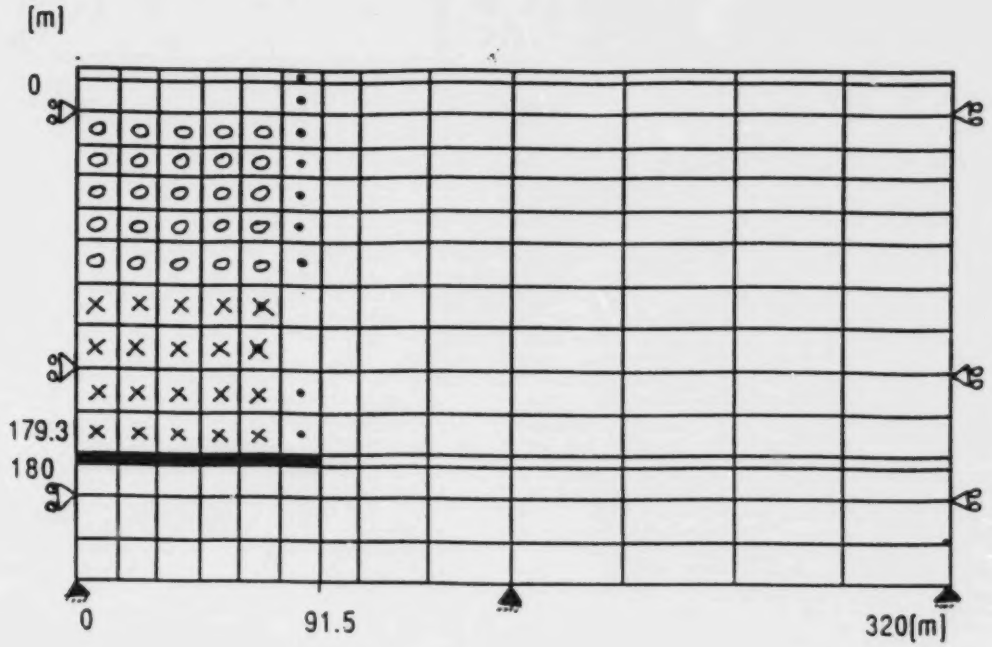

Figure 3. FEM Mesh and Boundary Conditions - Shoemaker Coal Mine
X - caved-in zone
o - anisotropic elements
• - boundary of the 'weak' zone

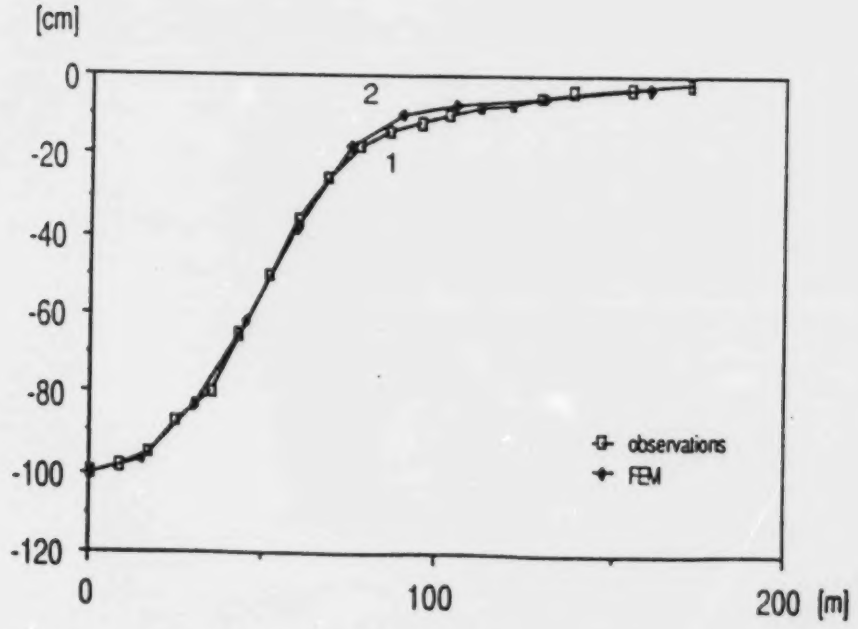

Figure 4. Calculated and Observed Subsidence - Shoemaker Coal Mine

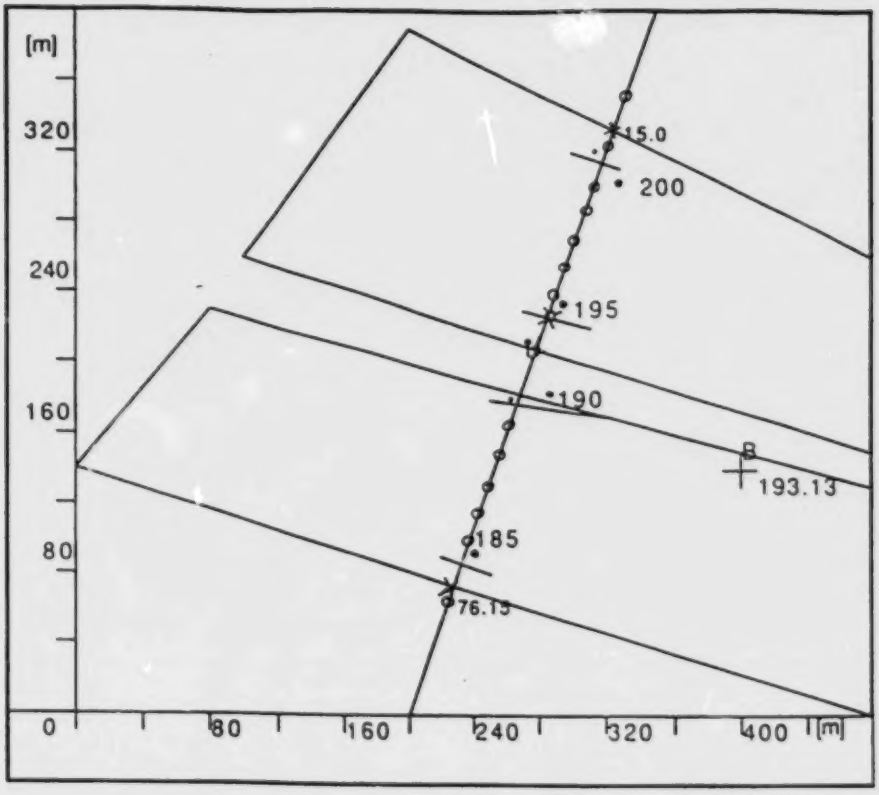

Figure 5. Coal Mine - East Coast People's Republic of China.
- geodetic subsidence surveys

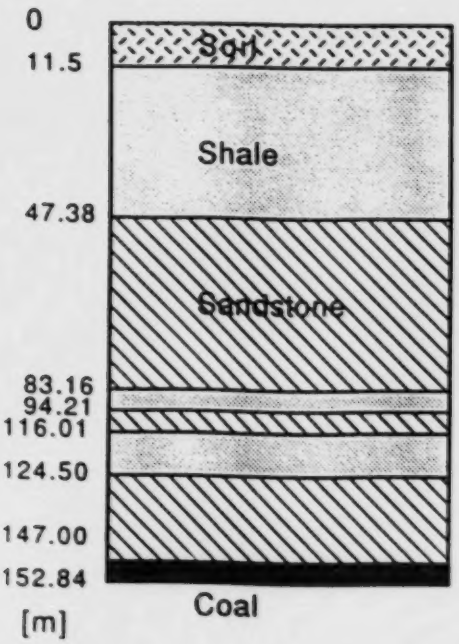

Figure 6. Geological Profile - Coal Mine in P. R. China

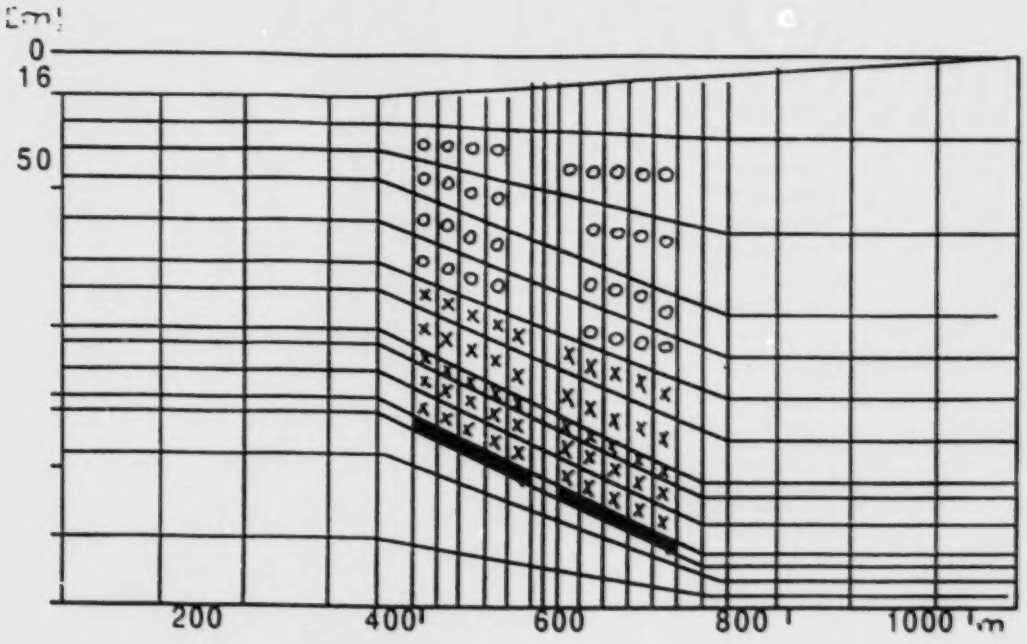

Figure 7. FEM Mesh - Coal Mine in P. R. China
x - caved-in zone
o - anisotropic elements
• - boundary of the 'weak' zone

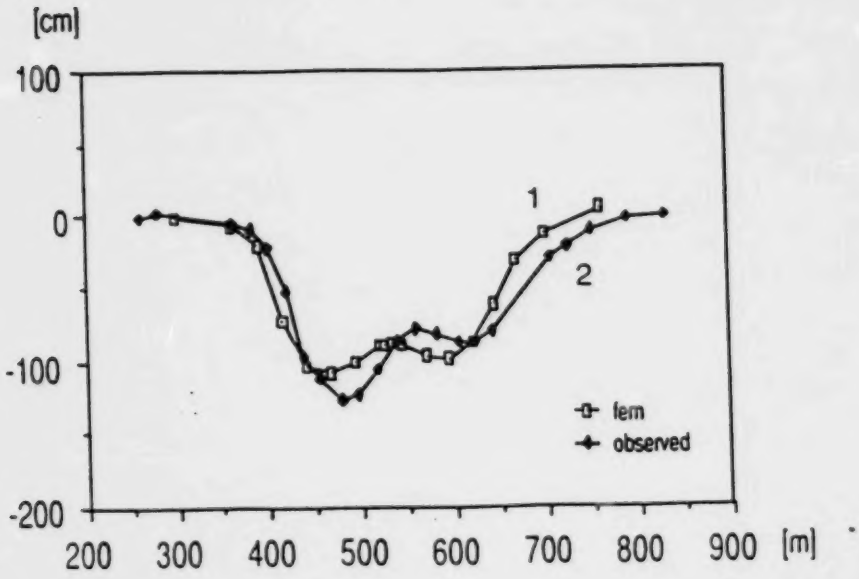

Figure 8. Calculated and Observed Subsidence - Coal Mine in P. R. China

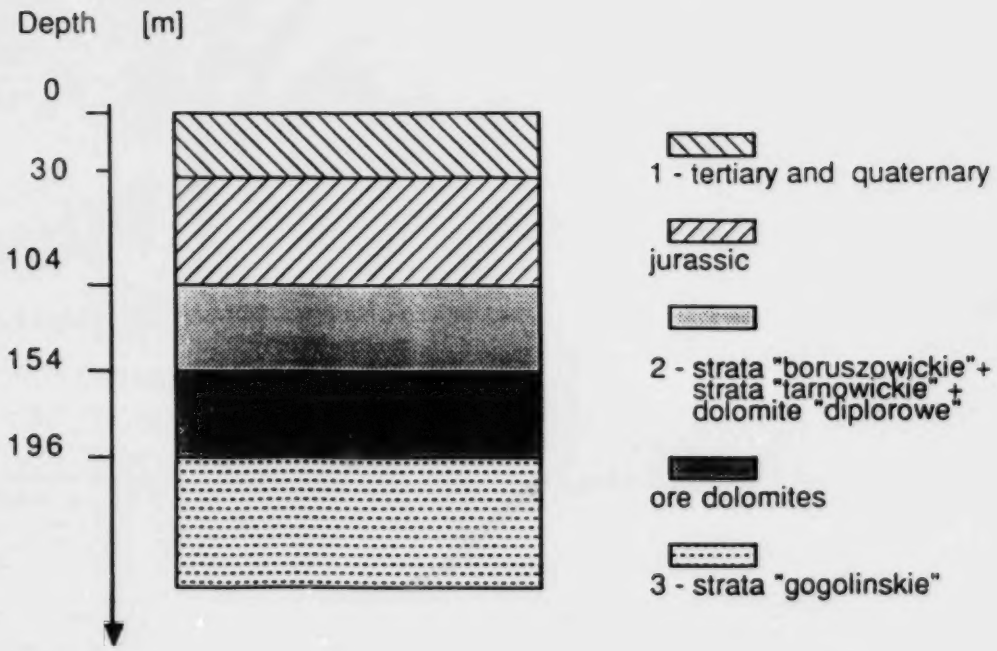

Figure 9. Geological Profile - Lead and Zinc Mine in Southern Poland

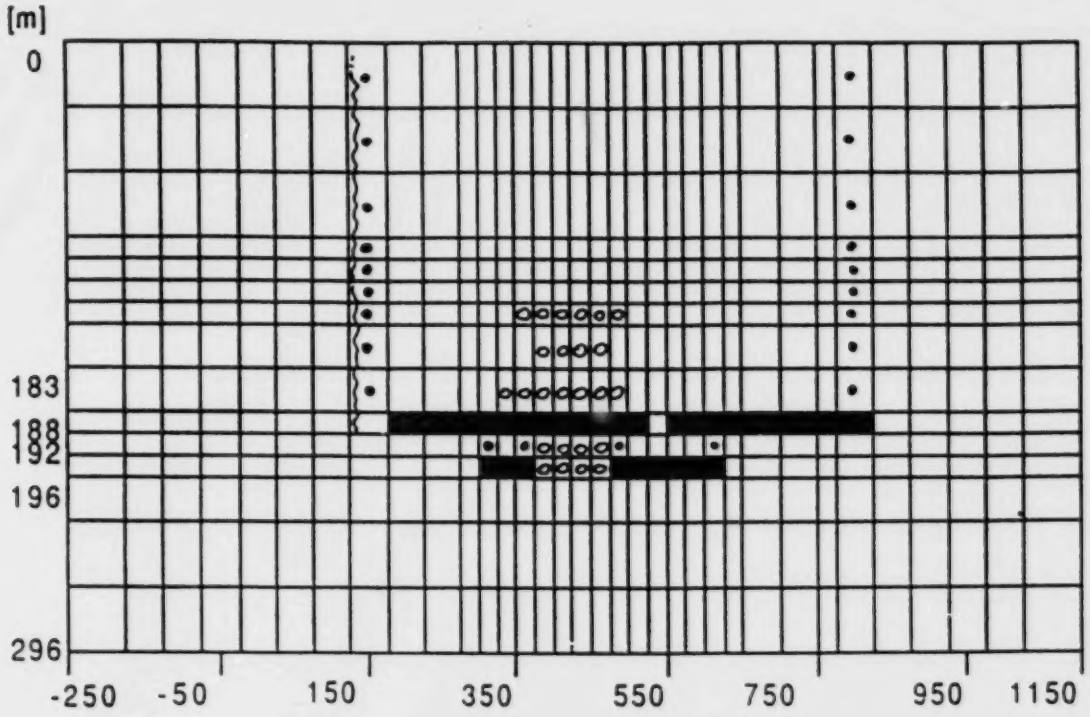

Figure 10. FEM Mesh - Lead and Zinc Mine in Poland

~~~ - fault zone

o - anisotropic elements

• - boundary of the 'weak' zone

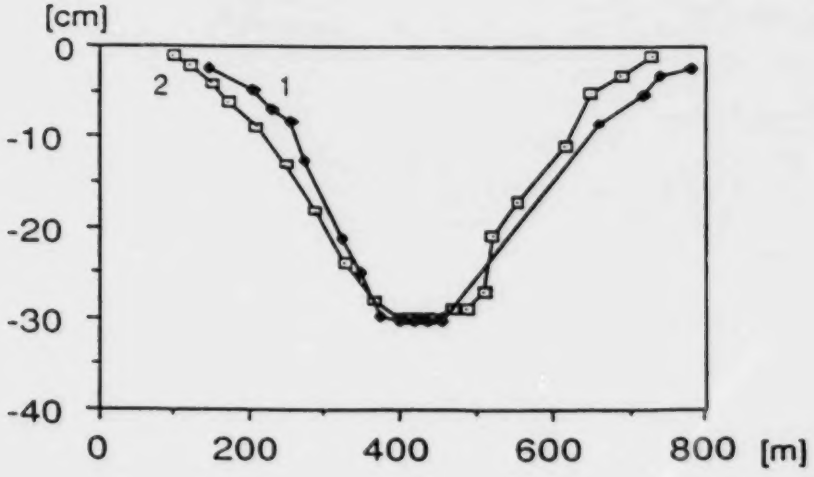

Figure 11. Calculated and Observed Subsidence - Lead and Zinc Mine in Poland
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APPENDIX B

UNB 1989 SURVEY CAMPAIGN

Report of Work and Results of
Surface Subsidence Monitoring Surveys
by
Department of Surveying Engineering, University of New Brunswick
1989 12

In accordance with Purchase Orders 39184 (1989 03 27) and 42246 (1989 10 27), work has been done in various surface surveys as a basis for the monitoring of subsidence over the McCully Station Road minesite near Sussex, New Brunswick for the Potash Company of America (PCA). The surveys can be distinguished as being of four types: horizontal (angles and distances); vertical (height differences); satellite Global Positioning System (GPS) baselines; and aerial photogrammetry. The major measurement effort occurred in 1989 05 (horizontal and vertical) and in 1989 10 (GPS).

Horizontal

A campaign was observed, 1989 05 13 - 19, to measure an assortment of spatial distances and horizontal angles - the distances for subsequent repetition and comparison and the angles and some of the distances to locate the stations on the profile lines as well as on the main loop containing the Trans-Canada Highway and the Canadian National railroad. The distances, reduced to the horizontal, are listed in Table 1 and have been plotted in Figure 1. Since intervisibility was not always possible between stations along a profile line (A.., B.., C.., D.., E..), several temporary stations (listed as "TEMP.." in the Table and marked with the symbol "X" in the plot) were used and consequently these distances will not likely be remeasurable. Any subsequent comparison for strain computation will utilize the remainder of the distances.

The distances were measured by a Kern DM503 distance meter mounted on a Kern E2 electronic theodolite which was used to measure the horizontal angles. In addition to the measurements at Sussex, the DM503 was calibrated from observations on the Mactaquac calibration baseline both before and after the campaign. As a consequence, a distance, s, using the DM503, has a standard deviation of σ_s according to

$$\sigma^2_s = a^2 + b^2 s$$

in which a = 0.003 m and b = 2.0 ppm. The repeating of distance measurements in 1990 05 will use a distance meter of much higher precision, a = 0.0003 m and b = 2.00 ppm (a Tellurometer model MA200 to be purchased by the Department in early 1990).

The horizontal angles will be utilized in 1990 05 along with connections to the stations

used in the GPS measurements, beyond the area of exploitation. This will enable an overall computation of coordinates encorporating all of the measurements.

Vertical

From 1989 05 13 - 20, height differences were measured using a Kern GK2-A precision automatic level with objective micromenter and using Kern 3 m invar levelling staves. Several loops were created, as shown in Figure 2, and incombination resulted in the adjusted elevations listed in Table 2. The elevations and their standard deviations are relative to the monument 10894, held fixed with an elevation of 22.230 m, to allow comparison with the survey by PCA.

These height differences, or a subset of them, are to be repeated in 1990 05.

GPS Baselines

On 1989 10 12,13 four stations were occupied by Ashtech 12 antennas and receivers (owned by the Department) to provide an initial set of four baselines, as shown in Figure 1 with the horizontal geodetic surveys. The results of this two day campaign are given in Table 3. As yet there is no connection from the network to monument 10482 by conventional survey.

These and additional baselines are to be measured in 1990 05 at which time the remaining horizontal and vertical connections to the network will be made.

Photogrammetry

Although there was a flight on 1989 05 21, the targets had not been placed on the monuments. The use of photographs, of this flight in particular, requires additional connections to identifiable points in order to properly provide orientation and scale. Nonetheless, comparison with later flights will still be possible.

Another flight is intended in 1990 05 during the horizontal, vertical and GPS surveys when connections and targetting will be done. After this, the photographs will be positioned in the overall coordinate system as mentioned above. Also, comparison with the 1989 05 flight will be possible.

PCA Sussex DM503 325147 on E2 345392 89 05 15-19. Ashtech 89 10 12.13

86 Stations
104 Distances or Baselines

NOTE: the following coordinates are for plotting only

STATION	Easting/x	Northing/y		
9635	387047.017	719935.449	3	0.0005
9636	386723.856	719790.068	3	0.0005
9637	385849.232	719151.276	3	0.0005
9638	385361.528	718601.316	3	0.0005
22797	386648.720	720148.829	3	0.0005
22798	384996.655	720025.691	3	0.0005
24739	383893.884	717519.426	3	
10894	383687.579	719963.155	3	0.0005
10482	390013.548	721246.462	3	
A7	384292.341	717869.484	4	0.0005
ML-21	384542.818	718028.245	4	0.0005
PCA8	384695.563	718100.468	2	0.0005
ML-20	384823.128	718198.627	4	0.0005
PCA9	384936.729	718285.366	2	0.0005
B7	384963.453	718413.831	4	0.0005
ML-19	385157.004	718465.649	4	0.0005
ML-18	385593.603	718840.626	4	0.0005
D7	386270.781	719519.392	4	0.0005
E6	387054.344	720063.856	4	0.0005
E5	387025.465	720180.835	4	0.0005
E1	386836.176	720845.642	4	0.0005
ML-17	386683.454	720856.338	4	0.0005
ML-15	386471.888	720829.510	4	0.0005
ML-14	386364.255	720851.419	4	0.0005
ML-13	386286.652	720904.478	4	0.0005
ML-12	386069.388	720862.145	4	0.0005
ML-11	385871.933	720809.764	4	0.0005
ML-10	385673.638	720742.027	4	0.0005
ML-9	385415.975	720650.853	4	0.0005
ML-8	385374.318	720421.711	4	0.0005
ML-7	385217.499	720245.542	4	0.0005
ML-6	385066.590	720089.322	4	0.0005
ML-5	384841.876	719900.730	4	0.0005
ML-4	384744.776	719760.422	4	0.0005
D1	384453.005	719531.445	4	0.0005
ML-3	384235.994	719363.101	4	0.0005
ML-2	384018.659	719194.240	4	0.0005
A1	383725.102	718803.420	4	0.0005
A2	383881.924	718861.863	4	0.0005
A3	383961.043	718715.161	4	0.0005
A4	384067.011	718516.886	4	0.0005
A5	384140.696	718373.409	4	0.0005
A6	384182.954	718160.564	4	0.0005
B3	384576.683	719221.280	4	0.0005
B4	384724.075	719008.224	4	0.0005
B5	384868.359	718795.774	4	0.0005
B6	384961.480	718599.142	4	0.0005
D6	386229.999	719667.108	4	0.0005
D5	386189.895	719810.070	4	0.0005
D4	386157.058	719940.004		0.0005
D3	386122.236	720090.666	4	0.0005

D2	386073.695	720205.236	4	0.0005
D1	386055.319	720346.661	4	0.0005
A8	384335.410	717689.762	4	0.0005
A9	384418.388	717502.274	4	0.0005
A10	384450.491	717363.804	4	0.0005
PCA6	384176.575	717772.263	2	0.0005
PCA7	384433.185	717938.755	2	0.0005
B2	384533.206	719326.386	4	0.0005
A11	384516.135	717180.922	4	0.0005
C2	385806.523	719280.144	4	0.0005
C1	385760.079	719450.173	4	0.0005
C4	385880.232	719013.758	4	0.0005
C5	385926.529	718853.480	4	0.0005
C6	385981.158	718647.238	4	0.0005
C7	386070.007	718370.502	4	0.0005
D8	386305.534	719391.528	4	0.0005
D9	386348.038	719250.298	4	0.0005
E7	387040.664	719780.713	4	0.0005
E8	387025.045	719553.493	4	0.0005
E9	387076.234	719345.559	4	0.0005
E10	387127.394	719060.782	4	0.0005
TEMP1	384354.362	719351.094	-5	0.0005
TEMP2	384290.412	717855.271	-5	0.0005
TEMP3	384355.696	717655.376	-5	0.0005
TEMP4	384416.754	717495.879	-5	0.0005
TEMP5	384453.106	717366.408	-5	0.0005
TEMP6	384494.591	717248.160	-5	0.0005
TEMP7	385319.741	718634.041	-5	0.0005
TEMP8	385809.344	719113.745	-5	0.0005
TEMP9	386788.670	720210.175	-5	0.0005
TEMP10	386202.584	720447.031	-5	0.0005
TEMP11	386508.487	720120.375	-5	0.0005
TEMP12	387011.216	719560.422	-5	0.0005
TEMP13	387030.798	719784.185	-5	0.0005
TEMP14	387063.827	719278.371	-5	0.0005

DISTANCES or BASELINES measured

NOTE: the following distances have been reduced to the horizontal

	FROM	TO	a	b	DISTANCE
1	E1	E5	0.0030	2.0000	691.2298
1	E1	ML-17	0.0030	2.0000	153.0961
1	ML-17	ML-15	0.0030	2.0000	213.2596
1	ML-15	ML-14	0.0030	2.0000	109.8402
1	ML-14	ML-13	0.0030	2.0000	94.0078
1	ML-13	ML-12	0.0030	2.0000	221.3498
1	ML-12	ML-11	0.0030	2.0000	204.2835
1	ML-11	ML-9	0.0030	2.0000	482.9556
1	ML-9	ML-7	0.0030	2.0000	451.2976
1	ML-9	ML-10	0.0030	2.0000	298.5431
1	ML-7	ML-6	0.0030	2.0000	217.2059
1	ML-6	22798	0.0030	2.0000	94.5273
1	22798	ML-5	0.0030	2.0000	198.9270
1	ML-5	ML-4	0.0030	2.0000	170.6306
1	ML-4	B1	0.0030	2.0000	370.8917
1	B1	B2	0.0030	2.0000	220.1852
1	ML-2	10894	0.0030	2.0000	403.9345

1	10894	A1
1	A1	A4
1	A4	A6
1	A4	A2
1	A4	A3
1	A4	A5
1	A6	A2
1	A6	A3
1	A6	A5
1	PCA8	9638
1	PCA8	ML-20
1	PCA8	PCA9
1	PCA8	ML-19
1	B6	B7
1	B7	B6
1	B7	B3
1	B7	B4
1	B7	B5
1	B7	B2
1	9638	9637
1	C6	C7
1	9637	C6
1	9637	C5
1	9637	C4
1	9637	9636
1	9637	22797
1	9636	D7
1	9636	D8
1	9636	D9
1	9636	9635
1	ML-9	ML-6
1	9638	9637
1	9637	9636
1	9636	9635
1	B7	B4
1	22798	ML-5
1	B1	TEMP1
1	TEMP1	ML-2
1	TEMP1	ML-3
1	TEMP2	A7
1	TEMP2	PCA6
1	TEMP2	PCA7
1	TEMP2	ML-21
1	TEMP2	A8
1	TEMP2	PCA8
1	A8	TEMP3
1	TEMP3	TEMP4
1	TEMP4	TEMP5
1	TEMP4	A9
1	TEMP5	TEMP6
1	TEMP5	A10
1	TEMP6	A11
1	9638	TEMP7
1	TEMP7	B6
1	TEMP7	B5
1	TEMP7	B4
1	TEMP7	B3
1	9637	TEMP8
1	TEMP8	ML-18
1	TEMP8	C1

0.0030	2.0000	164.0329
0.0030	2.0000	446.0976
0.0030	2.0000	374.7113
0.0030	2.0000	391.4917
0.0030	2.0000	224.8158
0.0030	2.0000	161.2933
0.0030	2.0000	763.1799
0.0030	2.0000	597.3469
0.0030	2.0000	217.0094
0.0030	2.0000	833.4888
0.0030	2.0000	160.9603
0.0030	2.0000	303.8894
0.0030	2.0000	588.4599
0.0030	2.0000	185.3250
0.0030	2.0000	185.3218
0.0030	2.0000	895.2759
0.0030	2.0000	640.7063
0.0030	2.0000	393.4214
0.0030	2.0000	1009.2571
0.0030	2.0000	735.1415
0.0030	2.0000	290.6491
0.0030	2.0000	521.0129
0.0030	2.0000	307.5882
0.0030	2.0000	140.9275
0.0030	2.0000	1083.1907
0.0030	2.0000	1278.6129
0.0030	2.0000	527.6002
0.0030	2.0000	577.7782
0.0030	2.0000	657.7156
0.0030	2.0000	354.4215
0.0030	2.0000	232.8979
0.0030	2.0000	735.1035
0.0030	2.0000	1083.1902
0.0030	2.0000	354.4266
0.0030	2.0000	640.7063
0.0030	2.0000	198.9270
0.0030	2.0000	205.5652
0.0030	2.0000	370.5403
0.0030	2.0000	118.9752
0.0030	2.0000	14.3436
0.0030	2.0000	140.8866
0.0030	2.0000	165.3898
0.0030	2.0000	305.9884
0.0030	2.0000	171.5178
0.0030	2.0000	473.5700
0.0030	2.0000	39.9236
0.0030	2.0000	170.7835
0.0030	2.0000	134.4779
0.0030	0.0000	6.6000
0.0030	2.0000	125.3141
0.0030	0.0000	3.6900
0.0030	2.0000	70.6049
0.0030	2.0000	53.1981
0.0030	2.0000	359.9563
0.0030	2.0000	479.4815
0.0030	2.0000	703.4420
0.0030	2.0000	947.0930
0.0030	2.0000	54.7686
0.0030	2.0000	348.0487
0.0030	2.0000	340.0160

1	TEMP8	C2	0.0030	2.0000	166.4231
1	TEMP8	C4	0.0030	2.0000	122.5671
1	TEMP8	C5	0.0030	2.0000	285.4301
1	TEMP8	C6	0.0030	2.0000	497.1410
1	22797	D5	0.0030	2.0000	570.3325
1	22797	D4	0.0030	2.0000	534.1710
1	22797	TEMP9	0.0030	2.0000	152.5853
1	TEMP9	E5	0.0030	2.0000	238.6087
1	TEMP9	E6	0.0030	2.0000	303.3016
1	22797	D3	0.0030	2.0000	529.6873
1	22797	TEMP10	0.0030	2.0000	526.6209
1	TEMP10	D1	0.0030	2.0000	178.2155
1	TEMP10	D2	0.0030	2.0000	274.0022
1	22797	TEMP11	0.0030	2.0000	143.0913
1	TEMP11	D6	0.0030	2.0000	531.9831
1	9636	D7	0.0030	2.0000	527.6002
1	9636	D8	0.0030	2.0000	577.8112
1	9636	D9	0.0030	2.0000	657.7724
1	9636	9635	0.0030	2.0000	354.4436
1	9635	TEMP12	0.0030	2.0000	376.6335
1	TEMP12	TEMP13	0.0030	2.0000	224.4846
1	TEMP12	E8	0.0030	2.0000	15.4681
1	TEMP13	E7	0.0030	2.0000	10.4791
1	TEMP12	E10	0.0030	2.0000	512.9698
1	E10	TEMP14	0.0030	2.0000	226.6839
1	TEMP14	E9	0.0030	2.0000	68.3236
1	A6	TEMP2	0.0030	2.0000	323.6530
1	9638	24739	0.003	2.00	1823.311
1	A1	C6	Ashtech GPS baseline		
1	A1	10482	Ashtech GPS baseline		
1	E1	10482	Ashtech GPS baseline		
1	E1	C6	Ashtech GPS baseline		

T1

Adjusted Elevations of UNB Campaign 1989 05 15-20
for
Potash Company of America, Sussex, New Brunswick

STATION	Elevation [m]	Standard Deviation [mm]
10894	22.2300	0.00 (held fixed)
9635	42.7130	0.5
9636	38.4494	0.4
9637(C3)	46.6868	0.4
9638	43.5681	0.4
22798	31.3805	0.3
68B205	28.1793	0.5
PCA7	24.6326	0.4
PCA8	30.2199	0.3
PCA9	27.1646	0.3
A1	21.8110	0.1
A2	22.4010	0.2
A3	21.9585	0.2
A4	21.3848	0.2
A5	21.8986	0.2
A6	22.4772	0.3
A7	27.6586	0.3
A8	29.6591	0.4
A9	30.2904	0.4
A10	33.2706	0.5
A11	41.8510	0.5
B1	28.3638	0.2
B2	28.9424	0.3
B3	21.4788	0.3
B4	21.7492	0.3
B5	21.3028	0.3
B6	21.5957	0.3
B7	28.4837	0.3
C1	38.3871	0.5
C2	42.5162	0.4
C3(9637)	46.6868	0.4
C4	43.7475	0.4
C5	40.5865	0.5
C6	45.3915	0.5
C7	36.4567	0.6

T2

STATION	Elevation [m]	Standard Deviation [mm]
D1	24.7104	0.4
D2	25.0566	0.4
D3	25.0002	0.4
D4	28.0058	0.4
D5	33.0887	0.4
D6	37.8755	0.4
D7	38.6904	0.4
D8	32.3997	0.5
D9	29.9192	0.5
D10	30.3633	0.5
E1	29.3153	0.5
E2	27.7924	0.5
E3	27.4052	0.5
E4	27.8451	0.5
E5	37.6806	0.5
E6	42.5472	0.5
E7	41.3120	0.5
E8	39.3492	0.5
E9	33.6650	0.6
E10	39.3807	0.7
ML2	25.2235	0.2
ML3	27.2076	0.2
ML4	26.7595	0.3
ML5	31.6574	0.3
ML6	32.9692	0.4
ML7	26.1244	0.4
ML8	26.6939	0.4
ML9	33.1525	0.4
ML10	27.6536	0.4
ML11	26.1139	0.4
ML12	26.5374	0.4
ML14	27.1423	0.4
ML15	28.5946	0.4
ML16	27.2562	0.4
ML17	30.1116	0.5
ML18	42.7823	0.4
ML19	36.5253	0.4
ML20	27.8121	0.3
ML21	27.1706	0.3

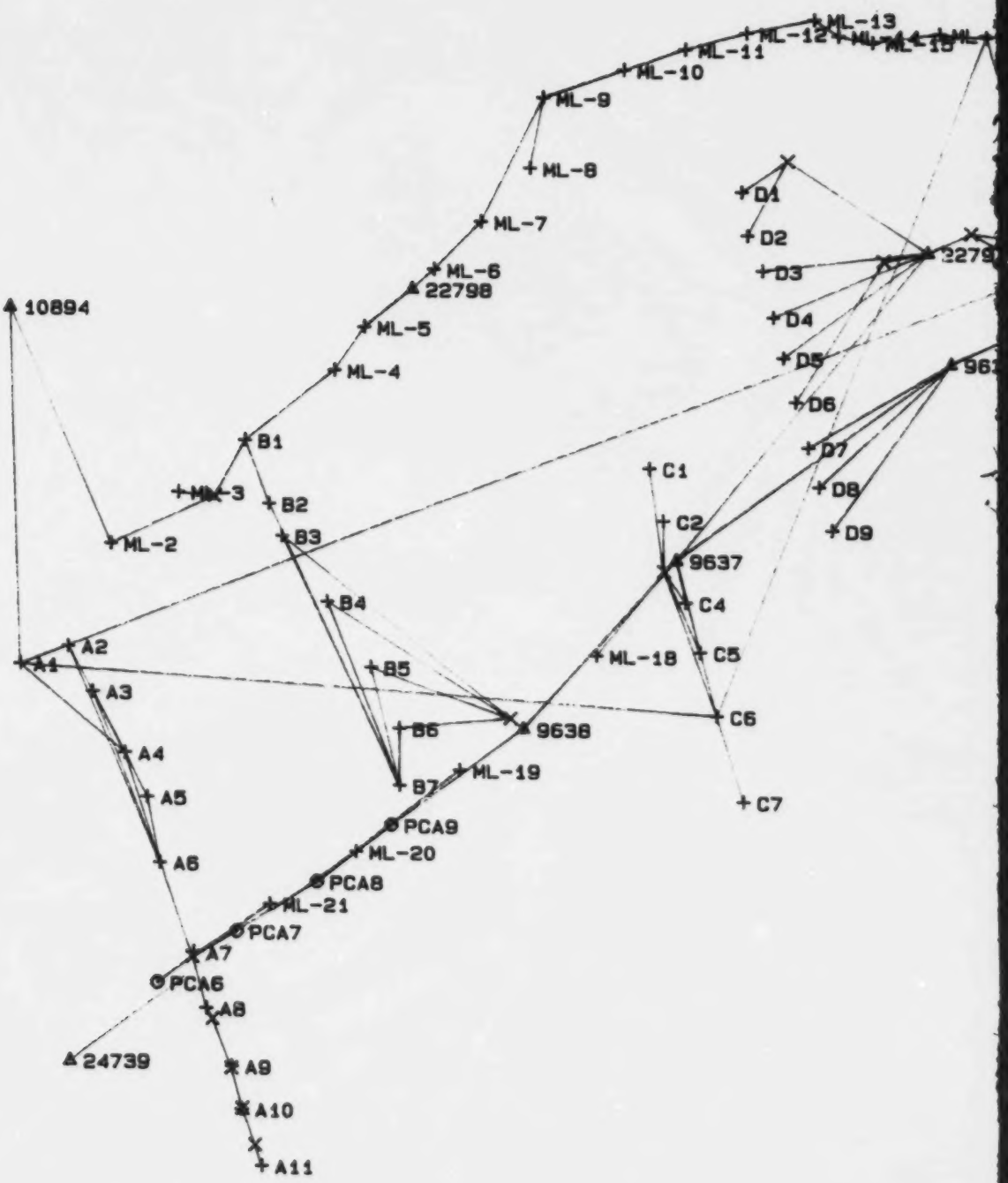
Baselines of Ashtech GPS Campaign 1989 10 12,13
for
Potash Company of America, Sussex, New Brunswick

Δφ (+ northerly)	Δλ (+ easterly)	Δh	D
From **C6** to **E1**			
1' 10".8019	0' 41".9845	- 16.041 m	2358.562 m
From **C6** to **A1**			
0' 06".0590	-1' 44".2934	- 23.625 m	2261.571 m
From **A1** to **10482**			
-1' 16".2659	4' 52".6479	34.168 m	6746.918 m
From **E1** to **10482**			
-0' 11".5234	2' 27".3704	26.549 m	3203.330 m

Δφ difference in latitude from the one end of the baseline to the other
Δλ difference in longitude from the one end of the baseline to the other
Δh difference in ellipsoidal height from the one end of the baseline to the other
D mark to mark slope distance between the two ends of the baseline

The C6 to E1 and C6 to A1 baselines were each observed for 80 minutes on 1989 10 12. The A1 to 10482 and E1 to 10482 baselines were observed for 80 and 75 minutes respectively on 1989 10 13.

The loop formed by all 4 baselines has a perimeter of 14.57 km and had a total misclosure of 38 mm.

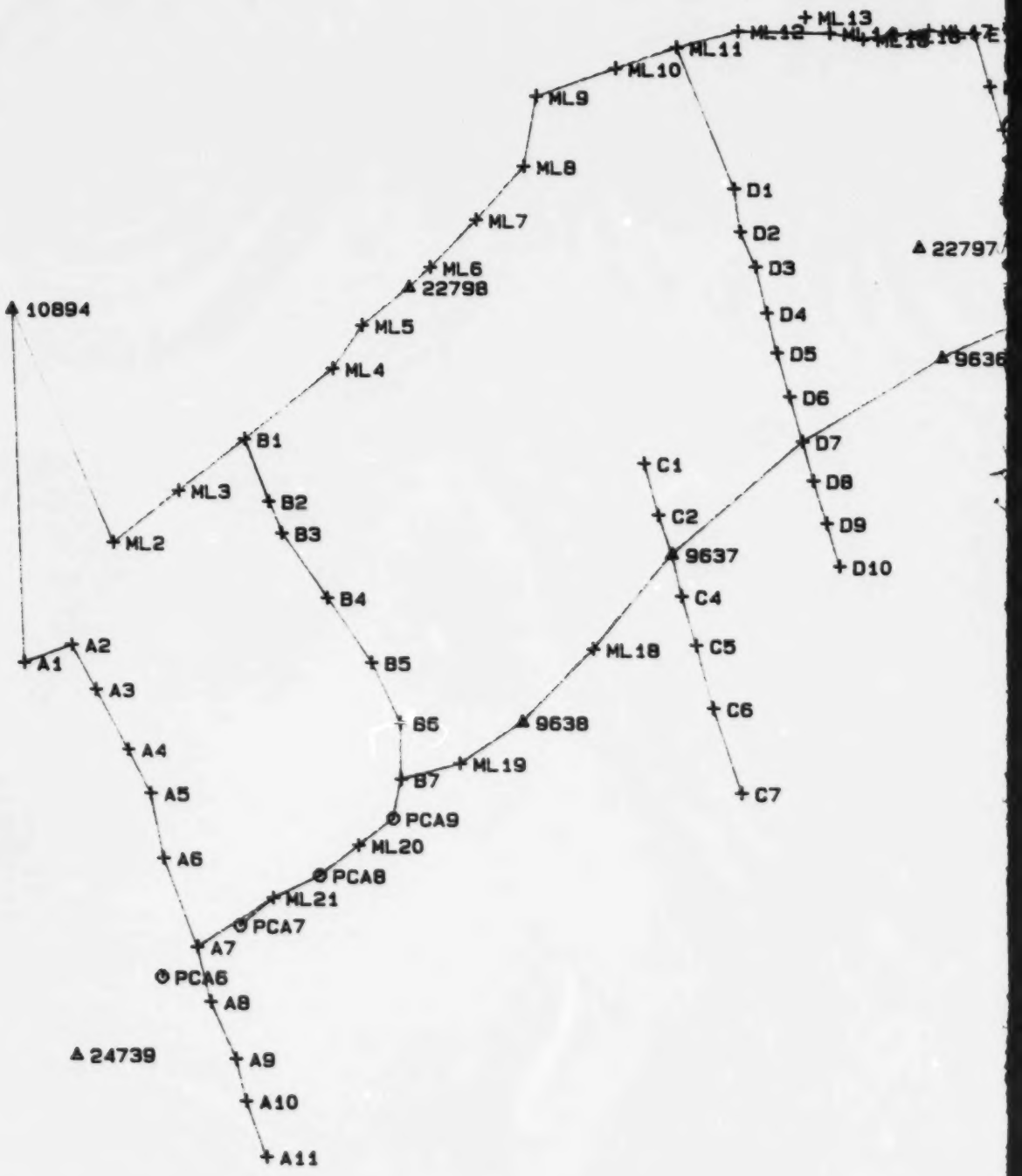


500. m

PCA Sussex DM503 325147 on E2 345392 89 05 15-19, Ashtech 89 10 12, 13

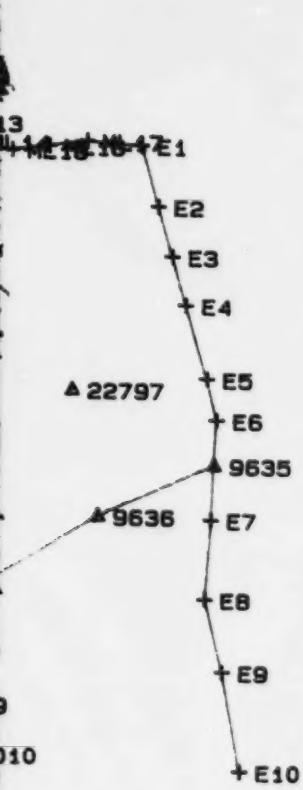
12, 13

F 1



500. m

PCA Sussex Levelling Lines (GK2-A with Invar staves) 1989 05 15-20



▲ 10482

15-20

F2

APPENDIX C

UNB 1990 SURVEY CAMPAIGN

Preliminary Report No.2
on Surface Subsidence Monitoring Surveys
by
Department of Surveying Engineering,
University of New Brunswick(UNB)
1990 07

In May 1990, UNB initiated the second survey campaign to monitor ground deformation in the area of PCA mining activity near Sussex, N.B., in accordance with Purchase Order No. 43749 of 1990 02 21.

The 1990 survey includes basically the same monitoring scheme, the same instrumentation and survey techniques, and the same survey stations as reported in 1989, with only a few additions and changes, namely:

(1) the vertical traversing has been extended to connect the main traverse loop (see attached plots) to the GPS station No. 10482

(2) stations D1 to D6 inclusive could not yet (as of June 30) be measured due to the high level of ground water in the area

(3) station HT has been added to the monitoring scheme by measuring additional horizontal and vertical angles, as well as distances from two stations of the main traverse.

(4) the GPS survey which is planned for the second half of July 1990 will be extended to include four more baselines to be measured from the new station HT

(5) about 15 ground targets were positioned for the new photogrammetric survey which was performed by Trainor Surveys in June 1990.

At the time of writing this report, the analysis of the horizontal terrestrial surveys has not yet been completed due to the delay in GPS measurements which will be integrated into a simultaneous analysis. Therefore, the preliminary results and comparison of 1989 and 1990 campaigns include only:

(a) comparison of heights and

(b) comparison of 51 distances between stations which have been common to both campaigns.

A brief discussion on the preliminary results follows.

Preliminary Results of Levelling and Heights Comparison

Tables 1 and 2 list heights of benchmarks as calculated from the1989 and 1990 survey campaigns respectively. Due to some mislabeling of benchmarks in 1989 one should disregard the table of heights given in the previous (1989) report. Table 3 gives changes in elevation between the two campaigns and their respective accuracies at the standard deviation and 95% confidence levels. The changes were calculated using two methods: first (Table 3a), holding the height of benchmark 68B205 as fixed and errorless in both campaigns and second (Table 3b), using the UNB generalized method of deformation analysis in which a weighted transformation of displacements is performed without holding any particular benchmark as fixed. The second method gives more reliable results because they are not biased by a possible movement of the constrained benchmark. Table 3b shows that the benchmark 68B205 may be subjected to a slight, though statistically insignificant, subsidence of -1.7 mm.

The results listed in Table 3b indicate that the benchmarks along the profiles 'A' (from A11 to 10894) are subject to an uplift of between 1 mm to 8 mm. Also benchmarks along the 'E' profile, particularly benchmarks E3 and E9, indicate an uplift trend of up to 6 mm. Benchmarks along profiles 'C' and 'D' show statistically significant average subsidence of -9 mm. Any meaningful interpretation of the results will be possible only after the1991 survey campaign if the shown trend continues. Hopefully, levelling of the remaining benchmarks along the 'D' profile will still be added during 1990. However, due to cultivation (ploughing) activity in the area some D benchmarks might have been disturbed.

Preliminary Comparison of 1990 and 1989 Distances

Table 4 lists 51 distances which were either directly measured in both campaigns or have been trigonometrically derived from measured angles and distances from temporary stations since,in many cases, the locations of the benchmarks do not have direct intervisibility. The estimated accuracy (at 95% probability) of the calculated changes in distances is 14 mm. Therefore, only those values in Table 4 which show larger than 14 mm changes have been considered as significant. Most of the shown values are within that confidence interval. The only exceptions are distances which include stations A6, B7, and ML2. At this stage one cannot say whether the changes are produced by actual ground movement or by local movement of the three monuments. Hopefully, further analysis of the whole monitoring network, including GPS surveys will allow for a more detailed interpretation. Perhaps, in 1991, or even later in 1990, UNB will use a more precise instrument (Tellurometer MA200) for distance measurements, at least between those monuments which are intervisible. The presently used Kern DM503 with its standard deviation of about 5 mm may not be accurate enough to detect horizontal strains in the subsidence area.

Preliminary Conclusions and Recommendations

A statistically significant ground movement has been detected between May 1989 and June 1990. The monitoring surveys should continue using the present (updated in 1990) monitoring scheme. Perhaps, a more accurate instrument for distance measurements should be used in the future surveys if funds become available. A correlation analysis between the monitored deformation values and the mining activitites should be performed after the next survey campaign in 1991.

The present cost of each survey campaign and its analysis is about $ 15,000. It is recommended that PCA seek funding for the 1991 campaign because UNB may not be able to subsidize the survey in 1991.

Fredericton, N.B., 1990 07 11

Adam Chrzanowski, P.Eng.

Table 1. Estimated Elevations of UNB Campaign 1989 05 15 to 20
for
Potash Company of America, Sussex, New Brunswick

Station	Elevation [m]	Standard Error [m]
A7	27.65856	0.00203
ML-21	27.17060	0.00199
PCA8	30.21989	0.00194
ML-20	27.81213	0.00190
PCA9	27.16458	0.00184
B7	28.48372	0.00177
ML-19	36.52530	0.00168
9638	43.56813	0.00158
ML-18	42.78229	0.00147
9637	46.68682	0.00130
D7	38.69040	0.00091
9636	38.44940	0.00129
9635	42.71297	0.00144
E6	42.54719	0.00150
E5	37.68056	0.00155
E4	27.84514	0.00162
E3	27.40525	0.00165
E2	27.79245	0.00166
E1	29.31529	0.00167
ML-17	30.11157	0.00167
ML-16	27.25620	0.00166
ML-15	28.59455	0.00166
ML-14	27.14232	0.00164
ML-13(ML-12)	26.53740	0.00161
ML-12(ML-11)	26.11392	0.00158
ML-11(ML-10)	27.65357	0.00163
ML-10(ML-9)	33.15254	0.00174
ML-9(ML-8)	26.69390	0.00179
ML-8(ML-7)	26.12435	0.00182
ML-7(ML-6)	32.96915	0.00186
22798	31.38053	0.00187
ML-6(ML-5)	31.65739	0.00188
ML-5(ML-4)	26.75954	0.00189
ML-4(B1)	28.36381	0.00188
ML-3	27.20757	0.00195
ML-2	25.22347	0.00200
10894	22.23000	0.00206

Station	Elevation [m]	Standard Error [m]
A1	21.81103	0.00207
A2	22.40095	0.00208
A3	21.95853	0.00209
A4	21.38480	0.00209
A5	21.89857	0.00209
A6	22.47722	0.00207
A8	29.65908	0.00215
A9	30.29045	0.00225
A10	33.27063	0.00232
A11	41.85096	0.00245
C2	42.51623	0.00141
C1	38.38712	0.00155
C4	43.74750	0.00141
C5	40.58646	0.00152
C6	45.39147	0.00165
C7	36.45671	0.00186
D8	32.39974	0.00112
D9	29.91920	0.00129
E7	41.31199	0.00151
E8	39.34921	0.00164
E9	33.66503	0.00182
E10	39.38068	0.00201
B2	28.94242	0.00199
B4	21.74921	0.00189
B5	21.30282	0.00186
B6	21.59569	0.00183
B3	21.47881	0.00191
D6	37.87551	0.00106
D5	33.08868	0.00118
D4	28.00579	0.00128
D3	25.00015	0.00138
D2	25.05661	0.00144
D1	24.71043	0.00149
PCA7	24.63260	0.00206
D10	30.36328	0.00137
68B205	28.17932	0.00000 (datum constraint)

Station names in parentheses are those used in the 1989 12 report of the 1989 levelling. In the comparison of the 1990 and 1989 levellings, benchmark 10894 was found to have significant movement. Therefore, benchmark 68B205 was used to define the datum for the adjustment of both campaigns for the comparison of 1990 and 1989. The value of its elevation was taken from the 1989 12 adjustment in order to maintain continuity of datum between the two reports (benchmark 10894 has the same elevation in both adjustments of the 1989 campaign).

Table 2. Estimated Elevations of UNB Campaign 1990 05 21 to 06 13
for
Potash Company of America, Sussex, New Brunswick

Station	Elevation [m]	Standard Error [m]
A7	27.66577	0.00255
ML-21	27.17530	0.00248
PCA8	30.22328	0.00242
ML-20	27.81437	0.00236
PCA9	27.16525	0.00229
B7	28.48418	0.00217
ML-19	36.52361	0.00203
9638	43.56174	0.00186
ML-18	42.77682	0.00173
9637	46.67705	0.00150
D7	38.68542	0.00107
9636	38.44849	0.00150
9635	42.71608	0.00166
E6	42.55102	0.00173
E5	37.68426	0.00180
E4	27.84839	0.00198
E3	27.41183	0.00203
E2	27.79527	0.00208
E1	29.31732	0.00213
ML-17	30.11326	0.00217
ML-15	28.59539	0.00229
ML-14	27.14363	0.00233
ML-13	26.53951	0.00239
ML-12	26.11540	0.00245
ML-11	27.65588	0.00250
ML-10	33.15451	0.00257
ML-9	26.69540	0.00261
ML-8	26.12398	0.00264
ML-7	32.96921	0.00268
22798	31.38045	0.00269
ML-6	31.65584	0.00270
ML-5	26.75702	0.00271
ML-4	28.36235	0.00272
B1	28.40429	0.00272
ML-3	27.20803	0.00272
ML-2	25.22662	0.00271
10894	22.23835	0.00269

Station	Elevation [m]	Standard Error [m]
A1	21.81999	0.00269
A2	22.41053	0.00268
A3	21.96885	0.00266
A4	21.38926	0.00264
A5	21.90170	0.00262
A6	22.48259	0.00259
A8	29.66657	0.00269
A9	30.29777	0.00279
A10	33.27857	0.00289
A11	41.85797	0.00304
C2	42.51205	0.00168
C1	38.38295	0.00184
C4	43.73895	0.00159
C5	40.58265	0.00168
C6	45.39165	0.00184
C7	36.43955	0.00206
D8	32.38992	0.00131
D9	29.91002	0.00152
E7	41.31488	0.00174
E8	39.35078	0.00190
E9	33.67268	0.00212
E10	39.38608	0.00231
B2	28.93865	0.00277
B4	21.74678	0.00254
B5	21.30738	0.00242
B6	21.60838	0.00230
10482	55.84918	0.00299
68B205	28.17932	0.00000 (datum constraint)

Table 3. PCA VERTICAL COMPARISON 1989 05 TO 1990 06

Table 3a. Displacements referred to Minimal Constraint, 68B208

(Positive is upward, negative is downward movement)

Station	DZ [mm]	Standard Error [mm]	95% Error [mm]
A7	7.22	3.26	6.39 **
ML-21	4.70	3.18	6.23 *
PCA8	3.39	3.11	6.09 *
ML-20	2.24	3.03	5.94
PCA9	0.67	2.94	5.76
B7	0.46	2.80	5.49
ML-19	-1.69	2.63	5.16
9638	-6.40	2.45	4.79 **
ML-18	-5.47	2.27	4.45 **
9637	-9.77	1.98	3.89 **
D7	-4.98	1.41	2.76 **
9636	-0.91	1.97	3.87
9635	3.10	2.20	4.31 *
E6	3.82	2.29	4.49 *
E5	3.70	2.38	4.66 *
E4	3.25	2.56	5.01 *
E3	6.58	2.61	5.12 **
E2	2.83	2.66	5.22 *
E1	2.03	2.70	5.30
ML-17	1.69	2.74	5.37
ML-15	0.83	2.83	5.54
ML-14	1.31	2.85	5.59
ML-13	2.11	2.88	5.65
ML-12	1.48	2.91	5.71
ML-11	2.32	2.99	5.86
ML-10	1.97	3.10	6.09
ML-9	1.49	3.16	6.20
ML-8	-0.37	3.20	6.28
ML-7	0.06	3.26	6.39
22798	-0.08	3.27	6.41
ML-6	-1.56	3.29	6.45
ML-5	-2.52	3.30	6.47
ML-4	-1.46	3.31	6.48
ML-3	0.46	3.34	6.56
ML-2	3.15	3.37	6.61
10894	8.34	3.39	6.65 **

A1	8.96	3.39	6.65 **
A2	9.58	3.39	6.65 **
A3	10.32	3.38	6.63 **
A4	4.46	3.37	6.60 *
A5	3.13	3.35	6.57
A6	5.37	3.31	6.50 *
A8	7.50	3.44	6.75 **
A9	7.33	3.58	7.03 **
A10	7.95	3.71	7.26 **
A11	7.02	3.90	7.65 *
C2	-4.18	2.19	4.30 *
C1	-4.17	2.41	4.72 *
C4	-8.55	2.13	4.17 **
C5	-3.81	2.26	4.44 *
C6	0.18	2.47	4.85
C7	-17.16	2.78	5.44 **
D8	-9.82	1.72	3.38 **
D9	-9.18	1.99	3.90 **
E7	2.88	2.31	4.52 *
E8	1.56	2.51	4.93
E9	7.64	2.79	5.47 **
E10	5.39	3.06	6.01 *
B2	-3.77	3.41	6.69 *
B4	-2.43	3.17	6.21
B5	4.56	3.06	5.99 *
B6	12.69	2.94	5.76 **
68B205	0.00	0.00	0.00

* Displacement beyond the bounds of the standard (68%) error interval
** Displacement beyond the bounds of the 95% error interval

Table 3b. Displacements after Weighted Transformation

(Positive is upward, negative is downward movement)

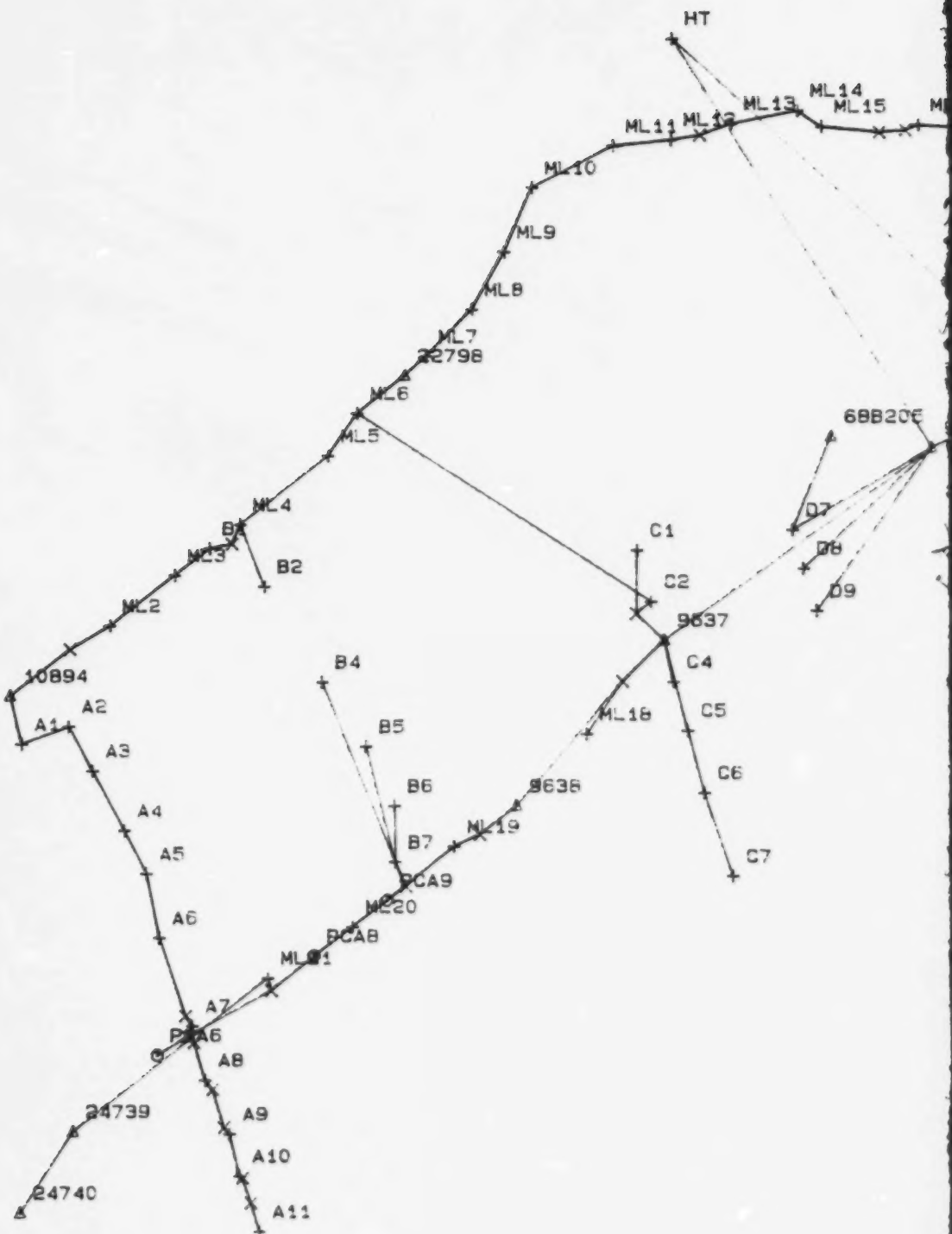
Station	DZ [mm]	Standard Error [mm]	95% Error [mm]
A7	5.52	2.88	5.64 *
ML-21	3.01	2.85	5.58 *
PCA8	1.70	2.81	5.51
ML-20	0.55	2.77	5.43
PCA9	-1.02	2.72	5.33
B7	-1.24	2.65	5.19
ML-19	-3.39	2.59	5.08 *
9638	-8.09	2.51	4.92 **
ML-18	-7.16	2.43	4.77 **
9637	-11.46	2.30	4.51 **
D7	-6.67	2.05	4.02 **
9636	-2.61	1.87	3.67 *
9635	1.41	1.73	3.39
E6	2.13	1.66	3.26 *
E5	2.01	1.58	3.10 *
E4	1.56	1.31	2.57 *
E3	4.89	1.17	2.30 **
E2	1.13	1.00	1.95 *
E1	0.33	0.77	1.51
ML-17	0.00	0.51	0.99
ML-15	-0.86	1.06	2.07
ML-14	-0.38	1.17	2.30
ML-13	0.42	1.37	2.69
ML-12	-0.21	1.52	2.98
ML-11	0.62	1.69	3.31
ML-10	0.27	1.93	3.79
ML-9	-0.20	2.07	4.05
ML-8	-2.07	2.18	4.27
ML-7	-1.64	2.34	4.58
22798	-1.77	2.38	4.66
ML-6	-3.25	2.45	4.81 *
ML-5	-4.21	2.52	4.93 *
ML-4	-3.15	2.60	5.09 *
ML-3	-1.23	2.68	5.26
ML-2	1.46	2.75	5.39
10894	6.65	2.83	5.55 **
A1	7.27	2.85	5.59 **
A2	7.89	2.87	5.63 **

A3	8.62	2.89	5.66 **
A4	2.77	2.90	5.69
A5	1.43	2.90	5.69
A6	3.68	2.90	5.68 *
A8	5.80	3.08	6.04 *
A9	5.63	3.24	6.35 *
A10	6.25	3.37	6.61 *
A11	5.32	3.59	7.03 *
C2	-5.87	2.48	4.87 **
C1	-5.86	2.68	5.24 **
C4	-10.24	2.42	4.75 **
C5	-5.50	2.54	4.99 **
C6	-1.51	2.73	5.35
C7	-18.85	3.01	5.89 **
D8	-11.51	2.28	4.47 **
D9	-10.87	2.49	4.87 **
E7	1.19	1.85	3.63
E8	-0.13	2.08	4.07
E9	5.95	2.41	4.72 **
E10	3.70	2.72	5.32 *
B2	-5.46	2.73	5.35 **
B4	-4.13	2.99	5.87 *
B5	2.87	2.89	5.66
B6	11.00	2.78	5.45 **
68B205	-1.69	2.48	4.87

* Displacement beyond the bounds of the standard (68%) error interval
** Displacement beyond the bounds of the 95% error interval

Table 4. PCA Distance Comparison 1989 05 to 1990 06

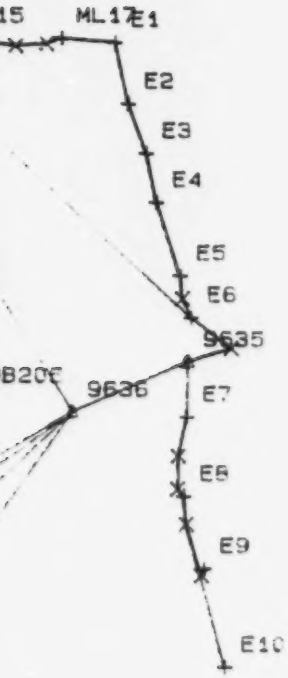
FROM	TO	DIST. (1990) [m]	DIST. (1989) [m]	ΔD(90-89) [mm]
E1	E5	691.142	691.150	-8
E1	E3	328.103	328.109	-6
E1	E4	472.052	472.041	+11
E1	E2	178.554	178.555	-1
E1	ML17	153.072	153.074	-2
ML15	ML14	93.973	93.977	-4
ML14	ML13	221.322	221.321	+1
ML13	ML12	204.261	204.256	+5
ML12	ML10	482.806	482.798	+8
ML10	ML8	451.257	451.243	+14
ML10	ML11	298.507	298.505	+2
ML8	ML7	217.177	217.177	0
ML7	22798	94.520	94.511	+9
22798	ML6	198.900	198.900	0
ML6	ML5	170.605	170.606	-1
ML5	ML4	370.847	370.846	+1
ML4	B2	220.145	220.156	-11
ML2	10894	403.874	403.893	-19
10894	A1	164.046	164.047	-1
A1	A4	446.044	446.044	0
A4	A6	374.653	374.665	-12
A4	A2	391.442	391.444	-2
A4	A3	224.781	224.786	-5
A4	A5	161.264	161.270	-6
A6	A2	763.068	763.093	-25
A4	A6	374.653	374.664	-11
A6	A3	597.258	597.277	-19
A6	A5	216.969	216.980	-11
PCA8	9638	833.381	833.394	-13
PCA8	ML20	160.932	160.937	-5
PCA8	PCA9	303.839	303.851	-12
PCA8	ML19	588.385	588.391	-6
B7	B6	185.286	185.296	-10
B7	B5	393.358	393.373	-15
B7	B2	1009.118	1009.144	-26
9638	9637	735.043	735.057	-14
C6	C7	290.512	290.504	+8
9637	C6	520.944	520.951	-7
9637	C5	307.541	307.549	-8
9637	C4	140.902	140.906	-4
9637	9636	1083.067	1083.070	-3
9636	D7	527.533	527.538	-5
9636	D8	577.708	577.711	-3
9636	9635	354.381	354.378	+3
ML10	ML9	232.864	232.867	-3
9637	9636	1083.067	1083.069	-2
9636	9635	354.381	354.383	-2
B7	B4	640.608	640.632	-24
22798	ML6	198.900	198.900	0
9636	9635	354.381	354.378	+3
9638	24739	1823.078	1823.086	-8



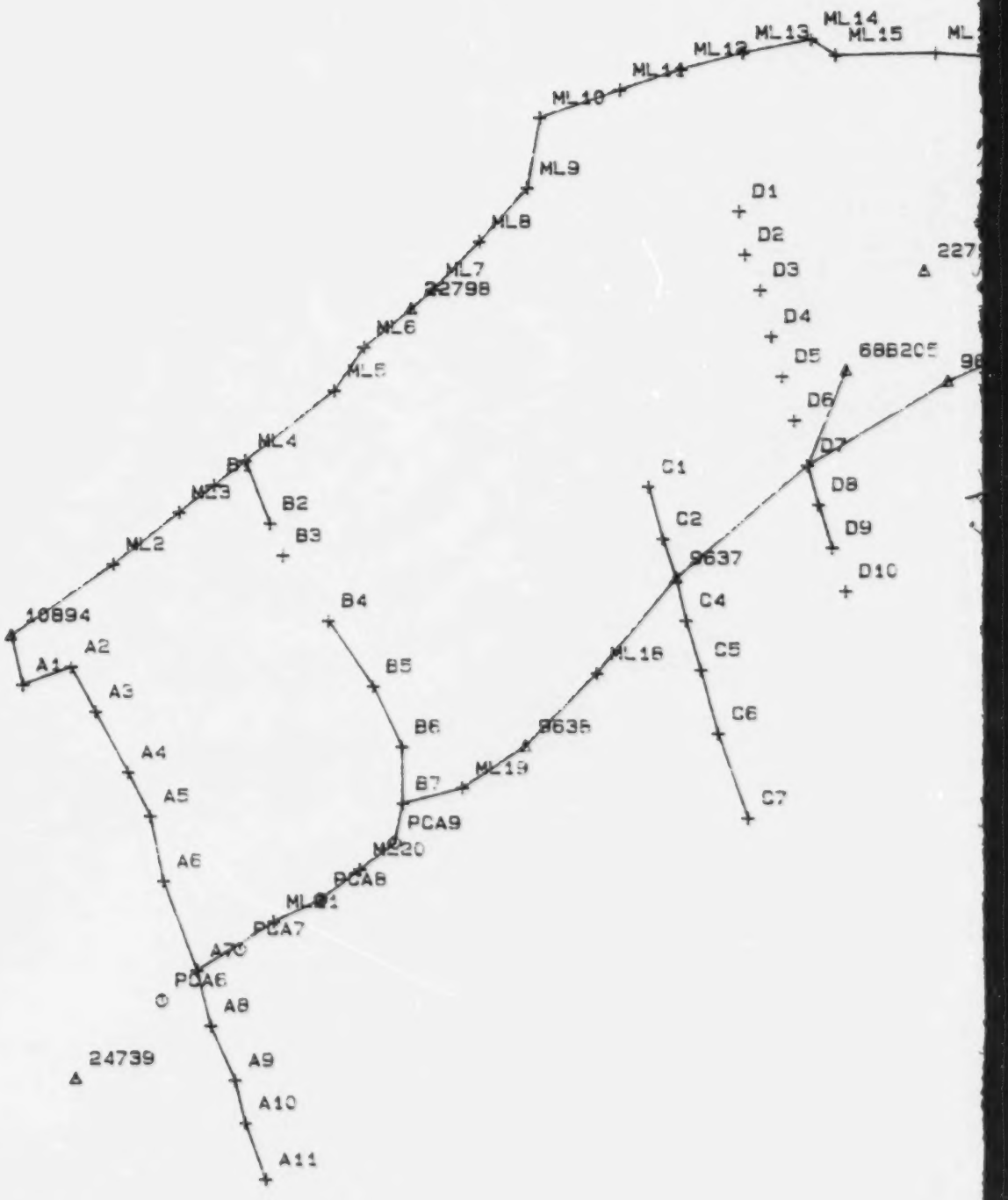
500 m

PCA Sussex DM503 348158 on E2 345392 1990 05 31 - 06 13, 25 PCAH90

10482



CAH90



500 m

PCA Sussex Levelling Lines (using Invar staves) 1990 05 21 to 06 13 PC

10482
L15
ML17
E1
E2
E3
E4
E5
22797
E6
E7
E8
E9
E10

APPENDIX D

REPORT ON SUBSIDENCE MONITORING AND PREDICTION AT A SASKATCHEWAN POTASH MINE

Introduction

In southeastern Saskatchewan, International Minerals and Chemical Corporation is mining potash, from the Esterhazy Member of the Prairie Evaporite Formation, at a depth of approximately 975 m. The Formation is about 100 m thick within which a 2.44 m thick ore zone is mined, typically leaving a salt back of 30 m between the mine workings and the overlying water bearing sediments.

Mining began at IMC's K1 mine in 1962, and at the adjoining K2 operation in 1967. By 1987, over 200 million tonnes of ore had been hoisted. With typical room-and-pillar mining extraction ranges from 10-40%, and long room-and-pillar, which is used in areas of K2, giving extraction of 25-55%. Differences in extraction are primarily due to the percentage of carnallite present. Typically, sylvinite ore in this area of the Province contains <5% carnallite. However, in placed this increased to >15%, necessitating a lower extraction ratio to maintain a manageable rate of closure while mining is taking place.

Subsidence Monument Network

466 surface subsidence monuments have been erected over some 100 sq. mls covering the mining area. This network is being extended by a further 120 monuments which are planned for the summer of 1990. Monuments are installed at the corner points of sections and at 1/2 ml or 1/4 ml intervals along section lines. The monuments are constructed by drilling a 12 ft X 4" hole and anchoring a rod in concrete at the bottom of the hole. The top of this rod acts as the survey monument and is protected from frost heave by an external sleeve which is free to move without interfering with the internal monument.

By law, annual surface subsidence surveys must be conducted above Saskatchewan mining operations. At IMC 15 such surveys were carried out between 1968 and 1988 using three different contractors. Such surveys typically take 4-6 weeks with a four man crew.

Subsidence Rates

Surface subsidence rates are in the order of

$$S_j = [E_{i,j} - E_{k,j}]/[t_i - t_k]$$

where S_j = sub rate at monument $_j$ (in mm/year)

$[E_{i,j} - E_{k,j}]$ = measured elevations (in mm) at $_j$ for surveys i&k

$[t_i - t_k]$ = times for surveys i&k (in years)

Underground subsidence rates in main entries are typically 15 mm/year and in the mining panels in the order of 100-200 mm/year.

Numerical Model

A numerical model consisting of two basic parts is being developed. A calculation is made of the subsidence caused by complete closure of a rectangular portion of the mine with a constant extraction ratio and mining height. The model then determines the rate of closure, in relation to time, of excavation and extraction ratio. The benchmark location, size and location of the mined areas and extraction ratio are used as input for the first part of the model with a number of parameters used to describe the time dependent properties of the rock units within and the above the mine.

The model allows an estimate to be made of the time required for closure to effect areas of differing extraction. The majority of the benchmarks are expected to have predicted subsidence and subsidence rates within 10% of that measured. The effect of geological features as indicated by surface lineaments is not always possible to predict, however, and predicted subsidence in such areas may differ significantly from that measured. Comparisons made between predicted and measured subsidence will allow fine tuning of the model, indicating the usefulness of a high quality subsidence monument network and good historical data.

APPENDIX E

TABLES SHOWING LEVELING RESULTS DECEMBER 1988 TO JUNE 1990

Date		Sta. A1 Reading	Movement	Rate/Year	Sta. A2 Reading	Movement	Rate/Year	Sta. A3 Reading	Movement	Rate/Year
01-Dec-88	0	21.8110			22.4010			21.9540		
01-May-89	151	21.8110	0.0000	0.0000	22.4010	0.0000	0.0000	21.9585	0.0045	0.0109
01-Oct-89	304	21.8110	0.0000	0.0000	22.4000	-0.0010	-0.0024	21.9560	0.0020	-0.0060
01-Jun-90	547	21.8200	0.0090	0.0135	22.4105	0.0095	0.0158	21.9689	0.0148	0.0193

		Sta. A4 Reading	Movement	Rate/Year	Sta. A5 Reading	Movement	Rate/Year	Sta. A6 Reading	Movement	Rate/Year
01-Dec-88	0	21.3700			21.8950			22.4500		
01-May-89	151	21.3848	0.0148	0.0358	21.8986	0.0036	0.0087	22.4772	0.0272	0.0657
01-Oct-89	304	21.3800	0.0100	-0.0115	21.8910	-0.0040	-0.0181	22.4770	0.0270	-0.0005
01-Jun-90	547	21.3893	0.0193	0.0139	21.9017	0.0067	0.0161	22.4826	0.0326	0.0084

		Sta. A7 Reading	Movement	Rate/Year	Sta. A8 Reading	Movement	Rate/Year	Sta. A9 Reading	Movement	Rate/Year
01-Dec-88	0	27.6560			29.6600			30.2940		
01-May-89	151	27.6586	0.0026	0.0063	29.6591	-0.0009	-0.0022	30.2904	-0.0036	-0.0087
01-Oct-89	304	27.6590	0.0030	0.0010	29.6630	0.0030	0.0093	30.2950	0.0010	0.0110
01-Jun-90	547	27.6658	0.0098	0.0102	29.6666	0.0066	0.0054	30.2978	0.0038	0.0042

		Sta. A10 Reading	Movement	Rate/Year	Sta. A11 Reading	Movement	Rate/Year
01-Dec-88	0	33.2740			41.8520		
01-May-89	151	33.2706	-0.0034	-0.0082	41.8509	-0.0011	-0.0027
01-Oct-89	304	33.2740	0.0000	0.0081	41.8510	-0.0010	0.0002
01-Jun-90	547	33.2786	0.0046	0.0069	41.8580	0.0060	0.0105

		B1 Reading	Movement	Rate/Year	B2 Reading	Movement	Rate/Year	B3 Reading	Movement	Rate/Year
01-Dec-88	0	28.3660			28.9400			21.4350		
01-May-89	151	28.3640	-0.0020	-0.0048	28.9420	0.0020	0.0048	21.4790	0.0440	0.1064
01-Oct-89	304	28.3640	-0.0020	0.0000	28.9410	0.0010	-0.0024	21.4750	0.0400	-0.0095
01-Jun-90	547	28.4043	0.0383	0.0605	28.9387	-0.0014	-0.0035			

		B4 Reading	Movement	Rate/Year	B5 Reading	Movement	Rate/Year	B6 Reading	Movement	Rate/Year
01-Dec-88	0	21.7770			21.2730			21.6030		
01-May-89	151	21.7490	-0.0280	-0.0677	21.3030	0.0300	0.0725	21.5960	-0.0070	-0.0169
01-Oct-89	304	21.7440	-0.0330	-0.0119	21.2430	-0.0300	-0.1431	21.5970	-0.0060	0.0024
01-Jun-90	547	21.7468	-0.0302	0.0042	21.3074	0.0344	0.0967	21.6084	0.0054	0.0171

		B7 Reading	Movement	Rate/Year
01-Dec-88	0	28.4890		
01-May-89	151	28.4840	-0.0050	-0.0121
01-Oct-89	304	28.4880	-0.0010	0.0095
01-Jun-90	547	28.4842	-0.0048	-0.0057

		C1			C2			C3		
		Reading	Movement	Rate/Year	Reading	Movement	Rate/Year	Reading	Movement	Rate/Year
01-Dec-88	0	38.5330			42.5630			46.7500		
01-May-89	151	38.3870	-0.1460	-0.3529	42.5160	-0.0470	-0.1136	46.6870	-0.0630	-0.1523
01-Oct-89	304	38.4110	-0.1220	0.0573	42.5390	-0.0240	0.0549	46.7100	-0.0400	0.0549
01-Jun-90	547	38.3830	-0.1501	-0.0421						

		C4			C5			C6		
		Reading	Movement	Rate/Year	Reading	Movement	Rate/Year	Reading	Movement	Rate/Year
01-Dec-88	0	43.8090			40.6390			45.4530		
01-May-89	151	43.7480	-0.0610	-0.1475	40.5870	-0.0520	-0.1257	45.3920	-0.0610	-0.1475
01-Oct-89	304	43.8100	0.0010	0.1479	40.6500	0.0110	0.1503	45.4470	-0.0060	0.1312
01-Jun-90	547	43.7390	-0.0700	-0.1067	40.5827	-0.0564	-0.1012	45.3917	-0.0614	-0.0831

		C7		
		Reading	Movement	Rate/Year
01-Dec-88	0	36.4810		
01-May-89	151	36.4570	-0.0240	-0.0580
01-Oct-89	304	36.4800	-0.0010	0.0549
01-Jun-90	547	36.4396	-0.0415	-0.0608

		D1 Reading	Movement	Rate/Year	D2 Reading	Movement	Rate/Year	D3 Reading	Movement	Rate/Year
01-Dec-88	0	24.6450			25.0590			25.0090		
01-May-89	151	24.7100	0.0650	0.1571	25.0570	-0.0020	-0.0048	25.0000	-0.0090	-0.0218
01-Oct-89	304	24.8630	0.2180	0.3650	25.2170	0.1580	0.3817	25.1590	0.1500	0.3793
01-Jun-90	547									

		D4 Reading	Movement	Rate/Year	D5 Reading	Movement	Rate/Year	D6 Reading	Movement	Rate/Year
01-Dec-88	0	28.0370			33.1460			37.9330		
01-May-89	151	28.0060	-0.0310	-0.0749	33.0890	-0.0570	-0.1378	37.8760	-0.0570	-0.1378
01-Oct-89	304	28.0750	0.0380	0.1646	33.1520	0.0060	0.1503	37.9370	0.0040	0.1455
01-Jun-90	547									

		D7 Reading	Movement	Rate/Year	D8 Reading	Movement	Rate/Year	D9 Reading	Movement	Rate/Year
01-Dec-88	0	38.7530			32.4660			29.9810		
01-May-89	151	38.6900	-0.0630	-0.1523	32.4000	-0.0660	-0.1595	29.9190	-0.0620	-0.1499
01-Oct-89	304	38.7660	0.0130	0.1813	32.4730	0.0070	0.1742	29.9920	0.0110	0.1742
01-Jun-90	547	38.6854	-0.0676	-0.1210	32.3899	-0.0761	-0.1248	29.9100	-0.0710	-0.1231

		D10 Reading	Movement	Rate/Year
01-Dec-88	0	30.4320		
01-May-89	151	30.3630	-0.0690	-0.1668
01-Oct-89	304	30.4390	0.0070	0.1813
01-Jun-90	547			

		E1			E2			E3		
		Reading	Movement	Rate/Year	Reading	Movement	Rate/Year	Reading	Movement	Rate/Year
01-Dec-88	0	29.3650			27.8420			27.4540		
01-May-89	151	29.3150	-0.0500	-0.1209	27.7920	-0.0500	-0.1209	27.4050	-0.0490	-0.1184
01-Oct-89	304	29.3680	0.0030	0.1264	27.8460	0.0040	0.1288	27.4560	0.0020	0.1217
01-Jun-90	547	29.3173	-0.0477	-0.0761	27.7953	-0.0467	-0.0762	27.4118	-0.0422	-0.0663

		E4			E5			E6		
		Reading	Movement	Rate/Year	Reading	Movement	Rate/Year	Reading	Movement	Rate/Year
01-Dec-88	0	27.8960			37.7380			42.6040		
01-May-89	151	27.8450	-0.0510	-0.1233	37.6810	-0.0570	-0.1378	42.5470	-0.0570	-0.1378
01-Oct-89	304	27.8970	0.0010	0.1241	37.7380	0.0000	0.1360	42.6080	0.0040	0.1455
01-Jun-90	547	27.8484	-0.0476	-0.0730	37.6843	-0.0537	-0.0807	42.5510	-0.0530	-0.0856

		E7			E8			E9		
		Reading	Movement	Rate/Year	Reading	Movement	Rate/Year	Reading	Movement	Rate/Year
01-Dec-88	0	42.7710			41.3700			39.4070		
01-May-89	151	42.7130	-0.0580	-0.1402	41.3120	-0.0580	-0.1402	39.3490	-0.0580	-0.1402
01-Oct-89	304	42.7770	0.0060	0.1527	41.3770	0.0070	0.1551	39.4090	0.0020	0.1431
01-Jun-90	547				41.3149	-0.0551	-0.0933	39.3508	-0.0562	-0.0874

		E10			E11		
		Reading	Movement	Rate/Year	Reading	Movement	Rate/Year
01-Dec-88	0	33.7240			39.4400		
01-May-89	151	33.6650	-0.0590	-0.1426	39.3810	-0.0590	-0.1426
01-Oct-89	304	33.7210	-0.0030	0.1336	39.4310	-0.0090	0.1193
01-Jun-90	547	33.6727	-0.0513	-0.0726	39.3861	-0.0539	-0.0675

		PCA 7 Reading	Movement	Rate/Year	PCA8 Reading	Movement	Rate/Year	PCA9 Reading	Movement	Rate/Year
01-Dec-88	0	24.6320			30.2230			27.1690		
01-May-89	151	24.6326	0.0006	0.0015	30.2200	-0.0030	-0.0073	27.1650	-0.0040	-0.0097
01-Oct-89	304	24.6350	0.0030	0.0057	30.2210	-0.0020	0.0024	27.1680	-0.0010	0.0072
01-Jun-90	547				30.2233	0.0003	0.0034	27.1653	-0.0038	-0.0041

		LRIS 9635 Reading	Movement	Rate/Year	LRIS 9637 Reading	Movement	Rate/Year	LRIS 9638 Reading	Movement	Rate/Year
01-Dec-88	0	42.7710			46.7500			43.6230		
01-May-89	151	42.7130	-0.0580	-0.1402	46.6870	-0.0630	-0.1523	43.5680	-0.0550	-0.1329
01-Oct-89	304	42.7770	0.0060	0.1527	46.7100	-0.0400	0.0549	43.5780	-0.0450	0.0239
01-Jun-90	547	42.7161	-0.0549	-0.0915	46.6771	-0.0729	-0.0495	43.5617	-0.0613	-0.0244

		ML2 Reading	Movement	Rate/Year	ML3 Reading	Movement	Rate/Year	ML4 Reading	Movement	Rate/Year
01-Dec-88	0	25.2200			27.2070			26.7680		
01-May-89	151	25.2230	0.0030	0.0073	27.2080	0.0010	0.0024	26.7600	-0.0080	-0.0193
01-Oct-89	304	25.2200	0.0000	-0.0072	27.2090	0.0020	0.0024	26.7810	0.0130	0.0501
01-Jun-90	547	25.2266	0.0066	0.0099	27.2080	0.0010	-0.0015	26.7570	-0.0110	-0.0360

		ML5 Reading	Movement	Rate/Year	ML7 Reading	Movement	Rate/Year	ML8 Reading	Movement	Rate/Year
01-Dec-88	0	31.6700			26.1630			26.7330		
01-May-89	151	31.6570	-0.0130	-0.0314	26.1240	-0.0390	-0.0943	26.6940	-0.0390	-0.0943
01-Oct-89	304	31.6830	0.0130	0.0620	26.1680	0.0050	0.1050	26.7390	0.0060	0.1074
01-Jun-90	547	31.6558	-0.0142	-0.0408	26.1240	-0.0390	-0.0661	26.6954	-0.0376	-0.0655

		ML10 Reading	Movement	Rate/Year	ML11 Reading	Movement	Rate/Year	ML12 Reading	Movement	Rate/Year
01-Dec-88	0	27.7000			26.1580			26.5800		
01-May-89	151	27.6540	-0.0460	-0.1112	26.1140	-0.0440	-0.1064	26.5370	-0.0430	-0.1039
01-Oct-89	304	27.7040	0.0040	0.1193	26.1630	0.0050	0.1169	26.5880	0.0080	0.1217
01-Jun-90	547	27.6559	-0.0441	-0.0723	26.1154	-0.0426	-0.0715	26.5395	-0.0405	-0.0728

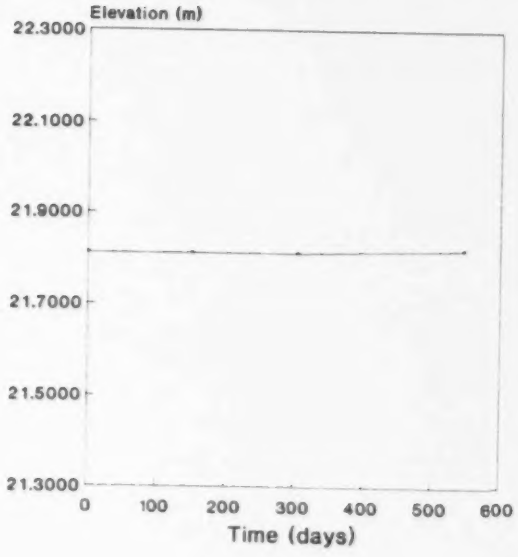
		ML16 Reading	Movement	Rate/Year	ML17 Reading	Movement	Rate/Year	ML18 Reading	Movement	Rate/Year
01-Dec-88	0	27.3010			30.1570			42.7960		
01-May-89	151	27.2562	-0.0448	-0.1083	30.1120	-0.0450	-0.1088	42.7820	-0.0140	-0.0338
01-Oct-89	304				30.1650	0.0080	0.1264	42.8040	0.0080	0.0525
01-Jun-90	547				30.1133	-0.0437	-0.0777	42.7768	-0.0192	-0.0408

		ML19 Reading	Movement	Rate/Year	ML20 Reading	Movement	Rate/Year	ML21 Reading	Movement	Rate/Year
01-Dec-88	0	36.5350			27.8140			27.1730		
01-May-89	151	36.5250	-0.0100	-0.0242	27.8120	-0.0020	-0.0048	27.1710	-0.0020	-0.0048
01-Oct-89	304	36.5300	-0.0050	0.0119	27.8130	-0.0010	0.0024	27.1730	0.0000	0.0048
01-Jun-90	547	36.5236	-0.0114	-0.0096	27.8144	0.0004	0.0021	27.1753	0.0023	0.0035

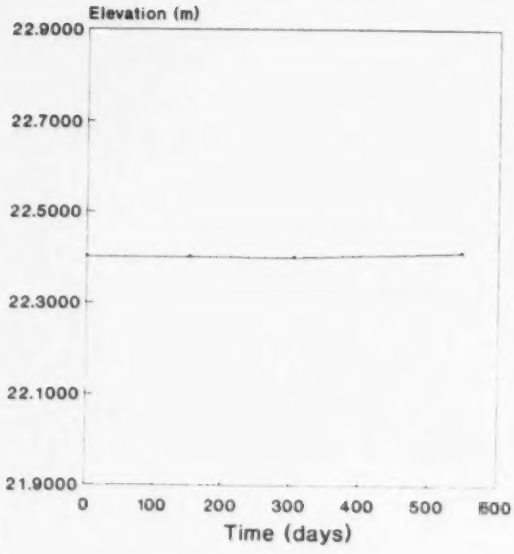
APPENDIX F

GRAPHS SHOWING MOVEMENT AT EACH SUBSIDENCE MONITORING STATION

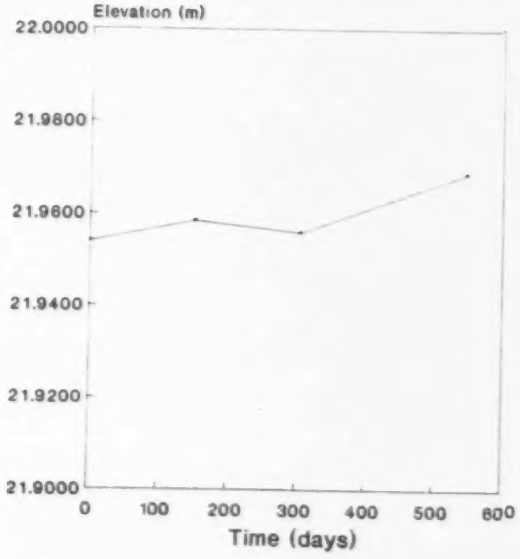
Subsidence Levels
Station 1A



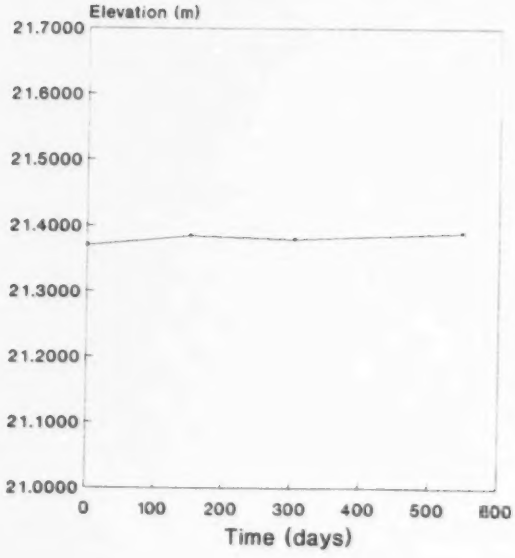
Subsidence Levels
Station 2A



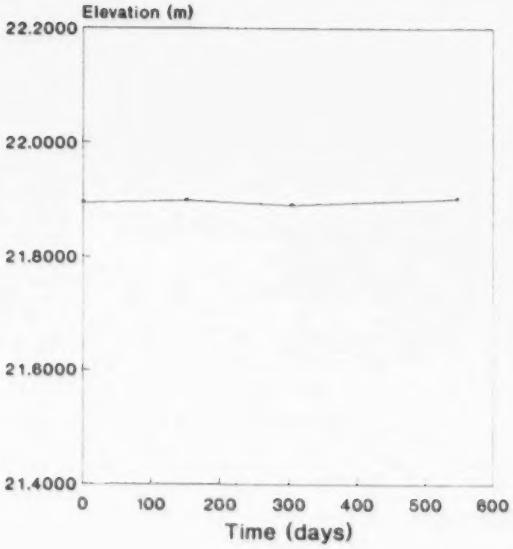
Subsidence Levels
Station 3A



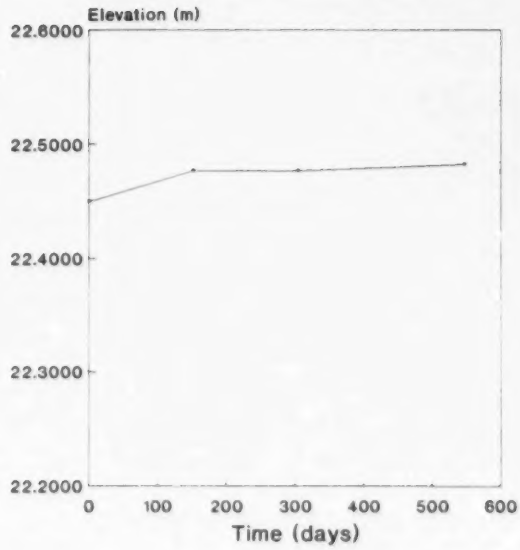
Subsidence Levels
Station 4A



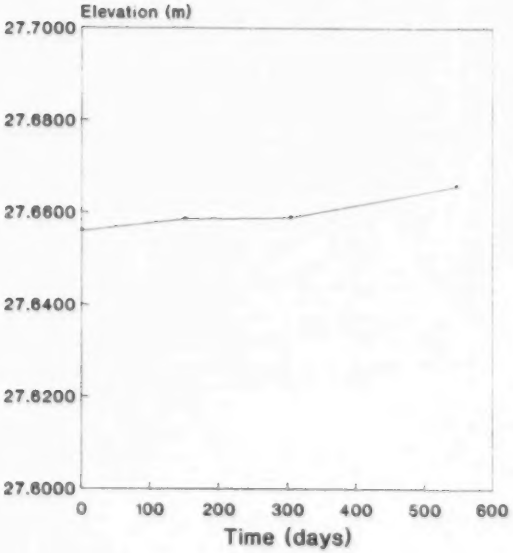
Subsidence Levels
Station 5A



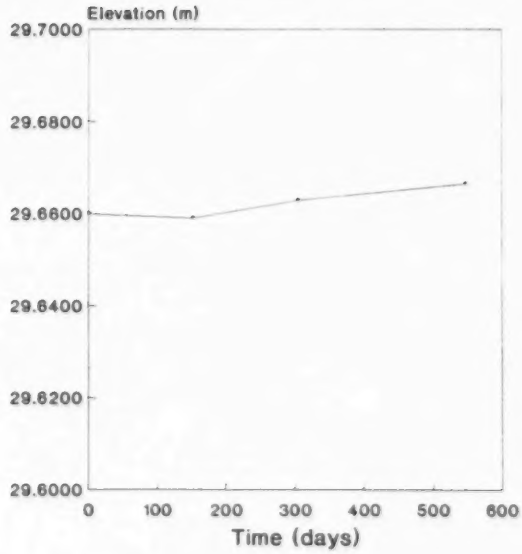
Subsidence Levels
Station 6A



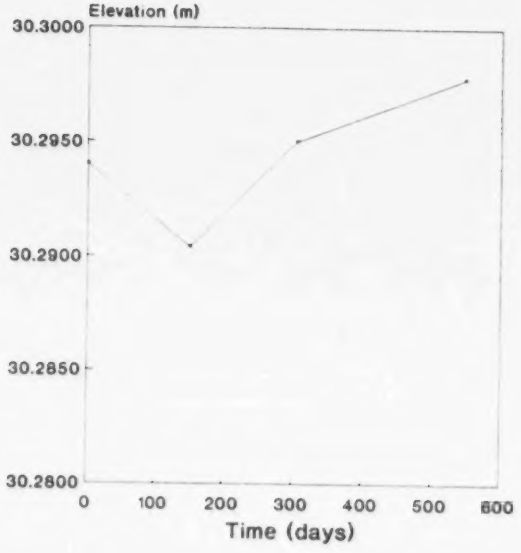
Subsidence Levels
Station 7A



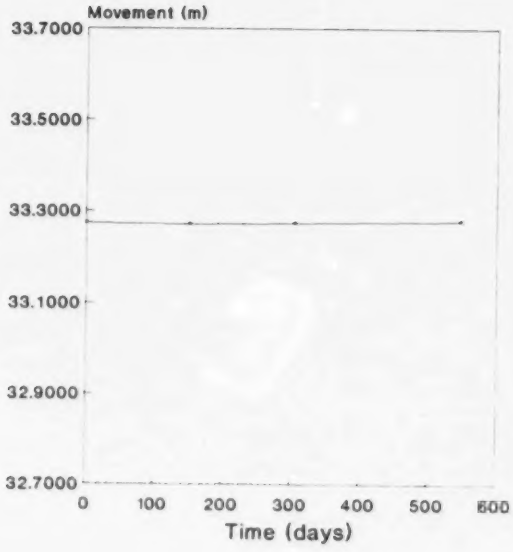
Subsidence Levels
Station 8A



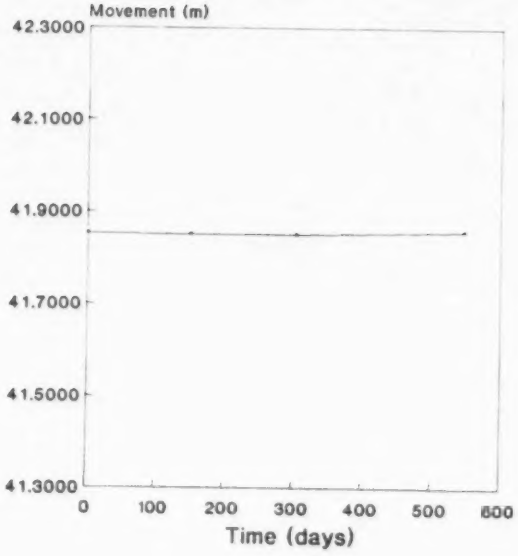
Subsidence Levels
Station 9A



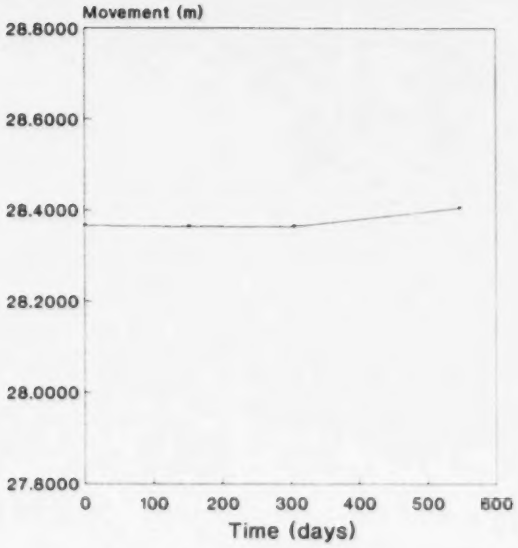
Subsidence Levels
Station 10A



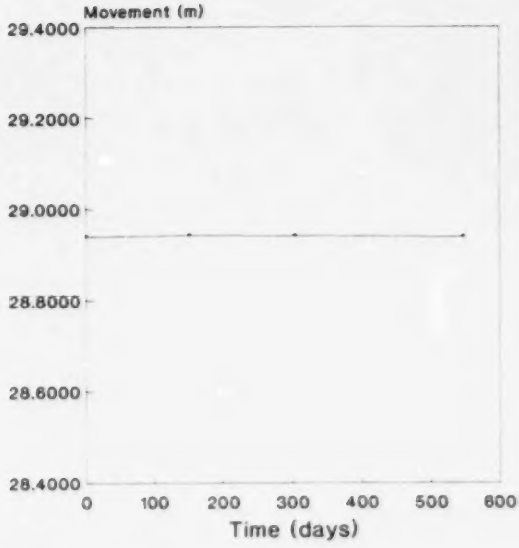
Subsidence Levels
Station 11A



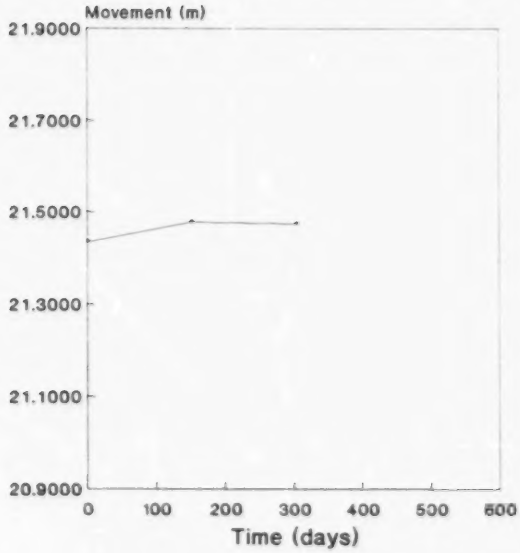
Subsidence Levels
Station B1



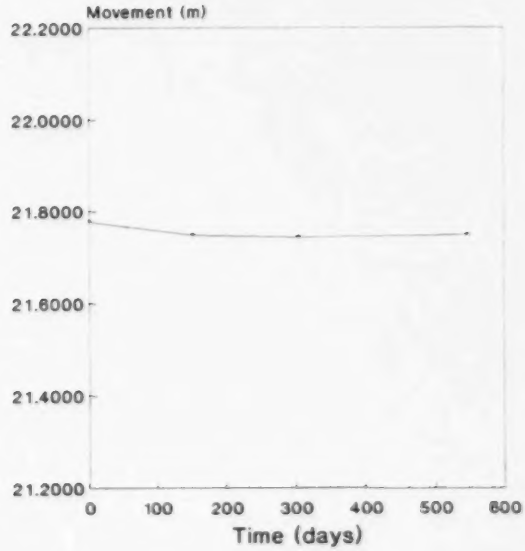
Subsidence Levels
Station B2



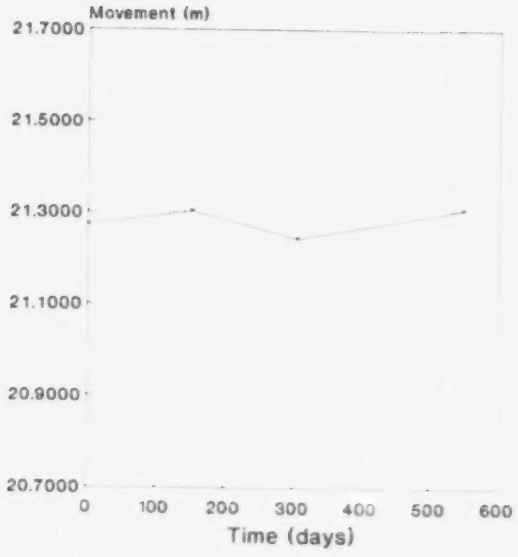
Subsidence Levels
Station B3



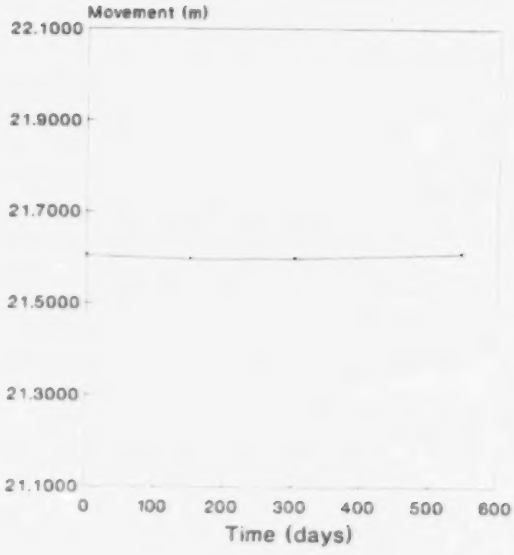
Subsidence Levels
Station B4



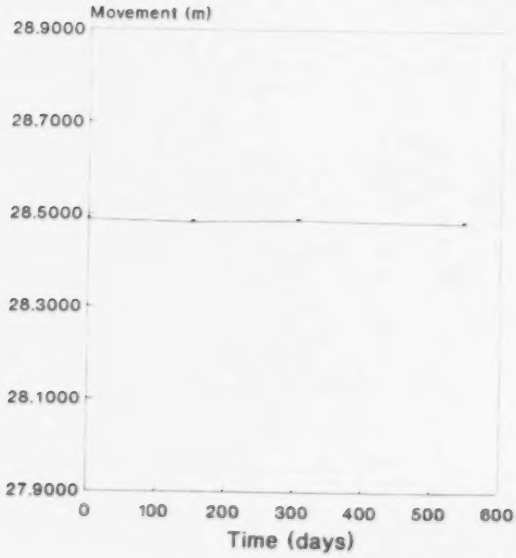
Subsidence Levels
Station B5



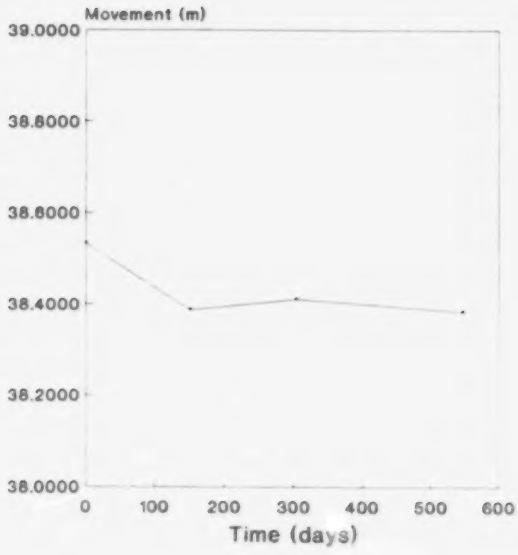
Subsidence Levels
Station B6



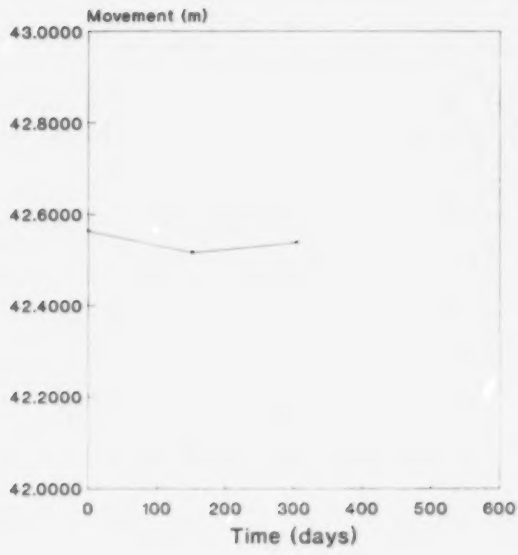
Subsidence Levels
Station B7



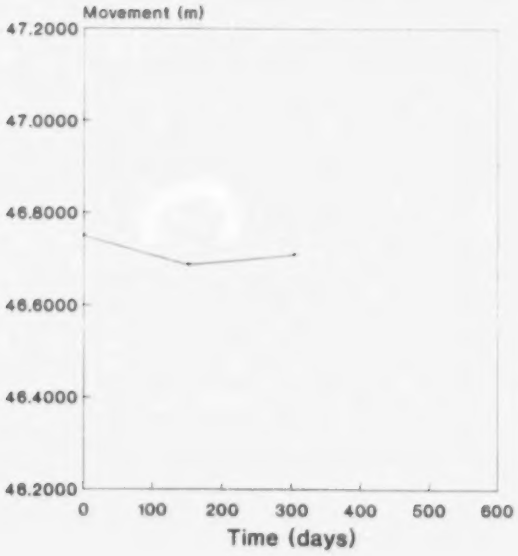
Subsidence Levels
Station C1



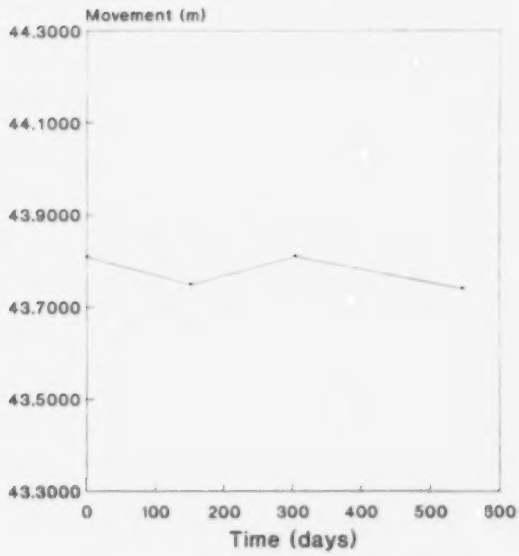
Subsidence Levels
Station C2



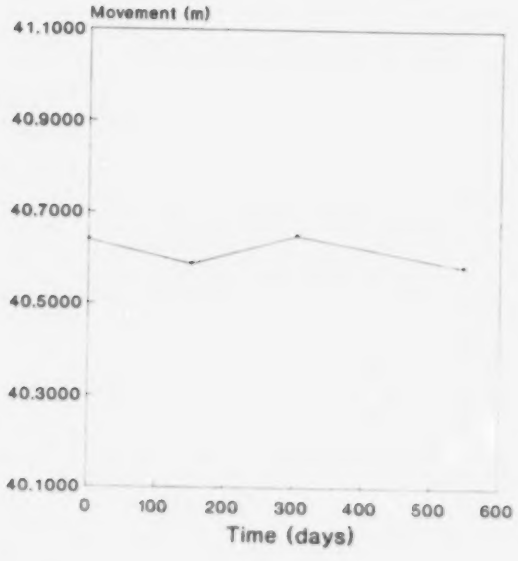
Subsidence Levels
Station C3



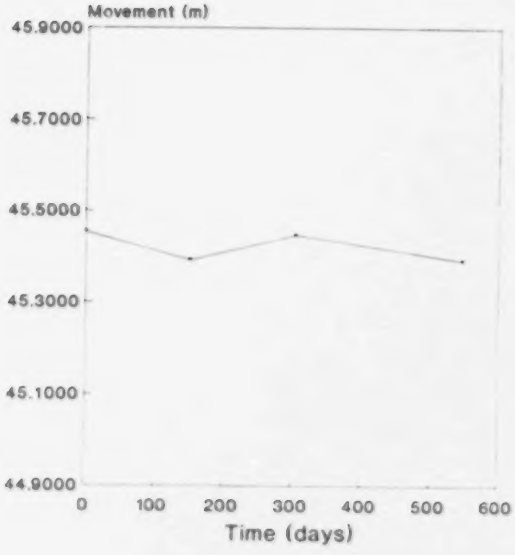
Subsidence Levels
Station C4



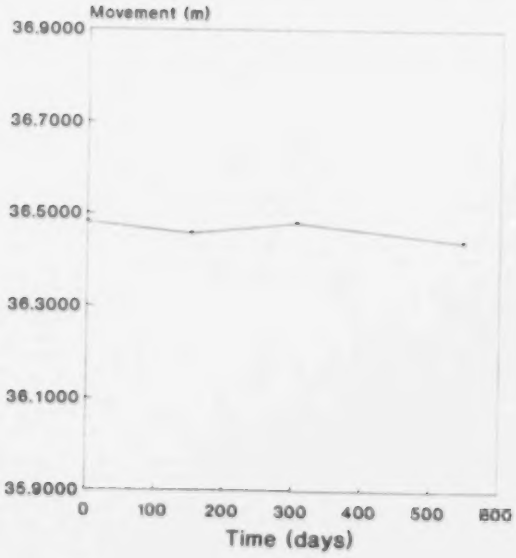
Subsidence Levels
Station C5



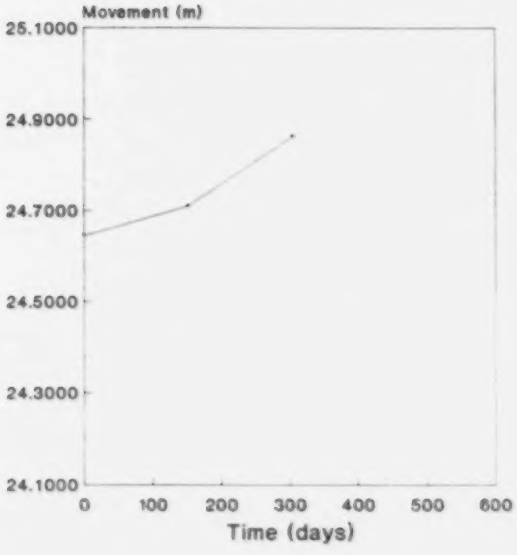
Subsidence Levels
Station C6



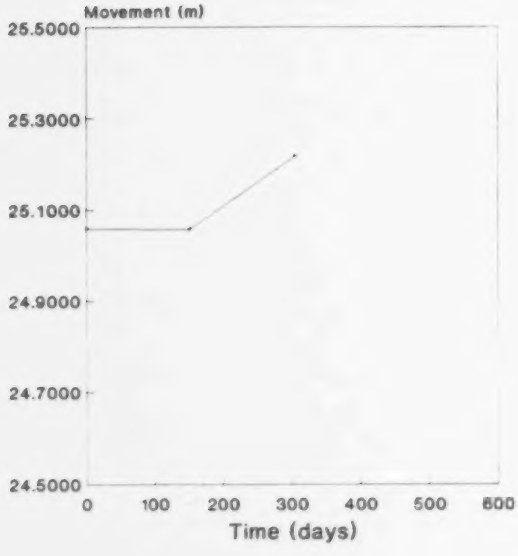
Subsidence Levels
Station C7



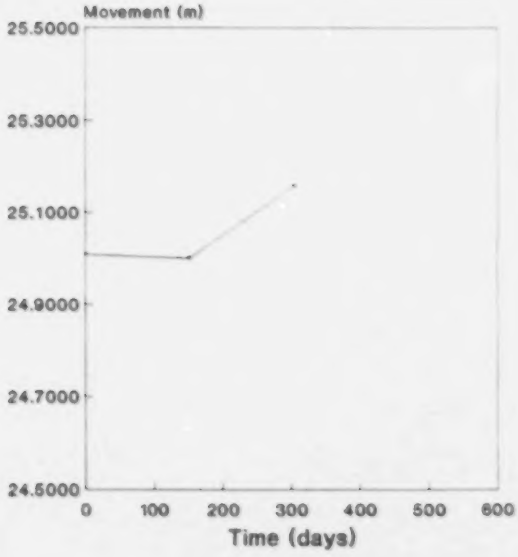
Subsidence Levels
Station D1



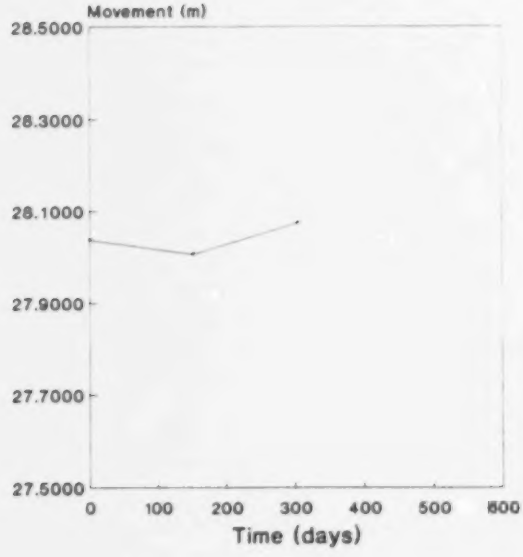
Subsidence Levels
Station D2



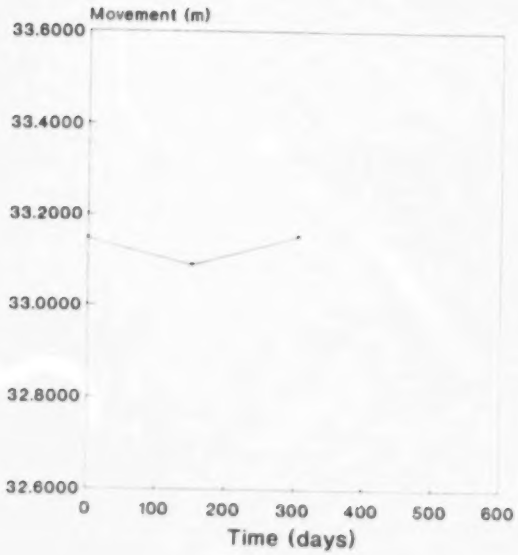
Subsidence Levels
Station D3



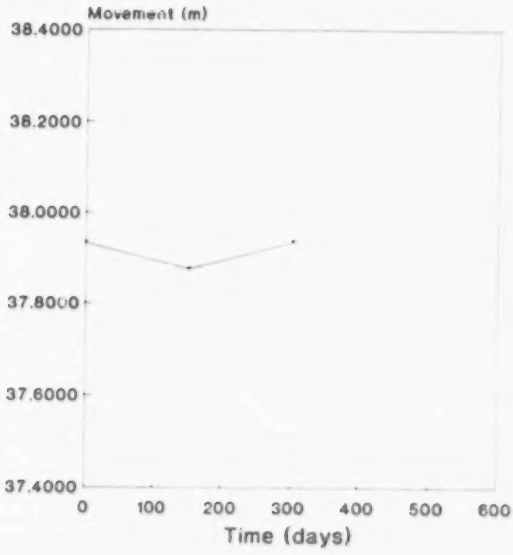
Subsidence Levels
Station D4



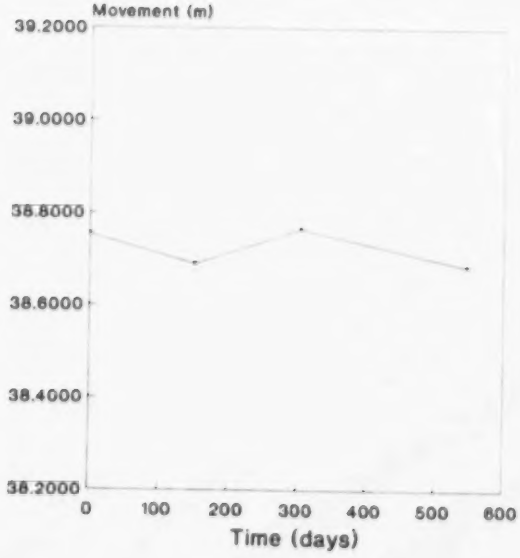
Subsidence Levels
Station D5



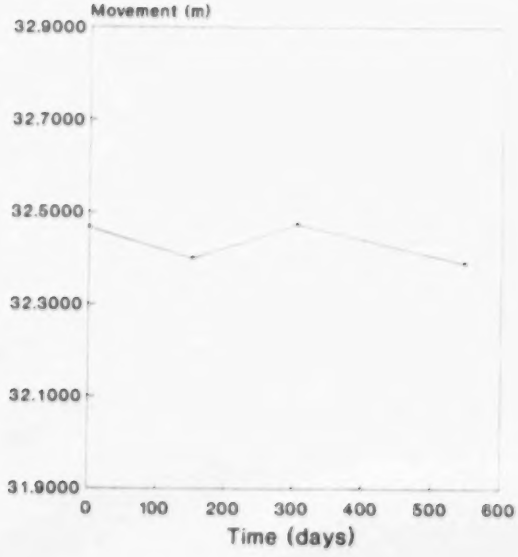
Subsidence Levels
Station D6



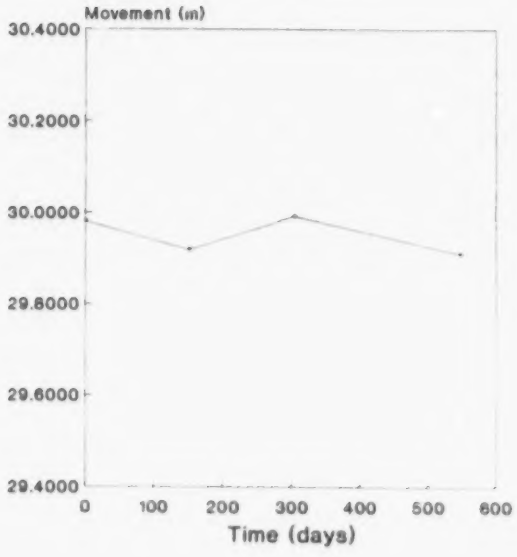
Subsidence Levels
Station D7



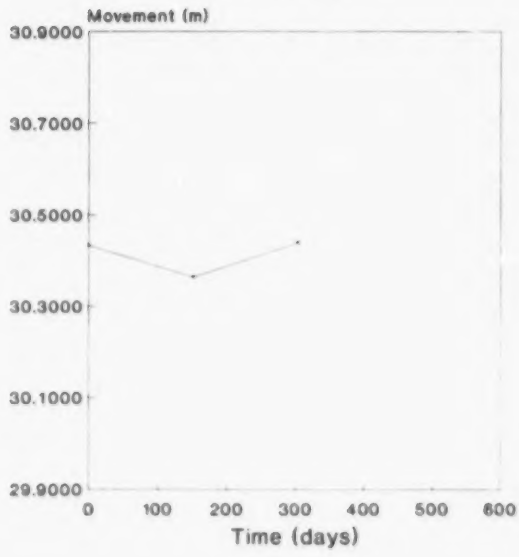
Subsidence Levels
Station D8



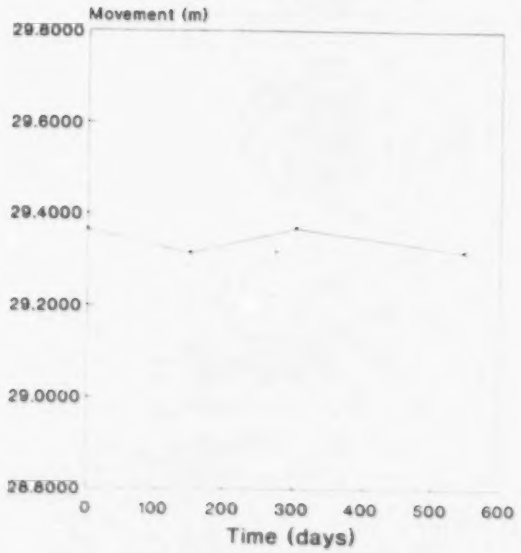
Subsidence Levels
Station D9



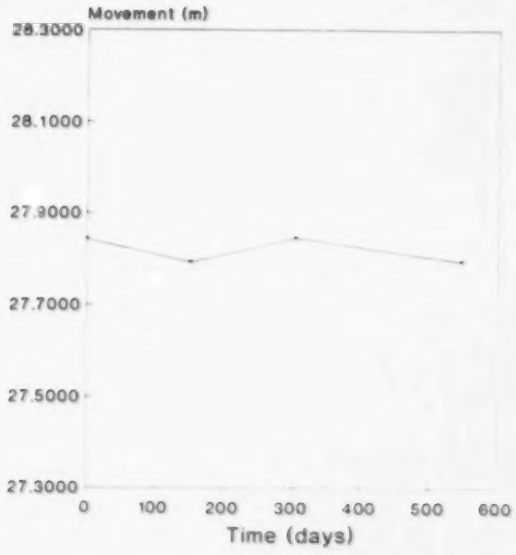
Subsidence Levels
Station D10



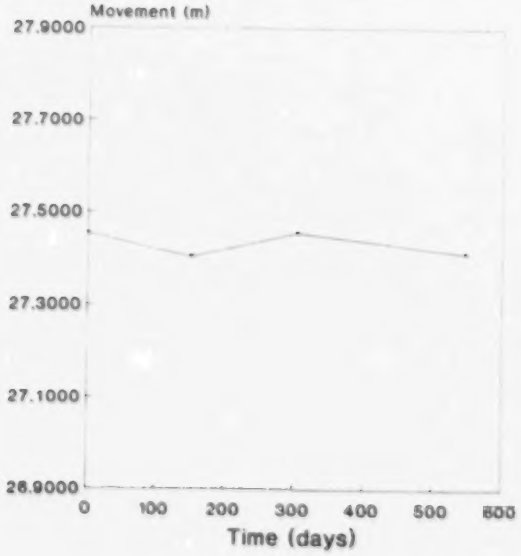
Subsidence Levels
Station E1



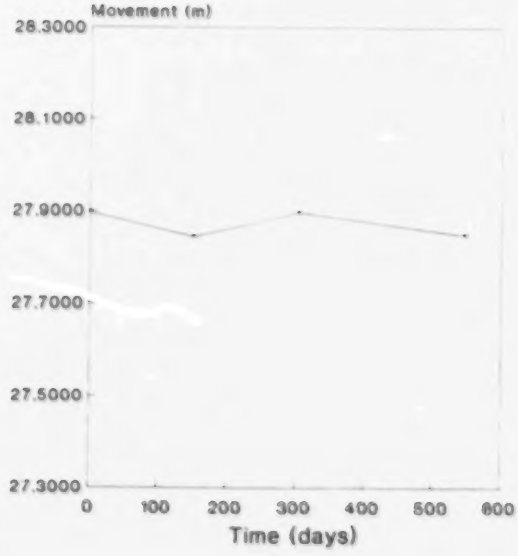
Subsidence Levels
Station E2



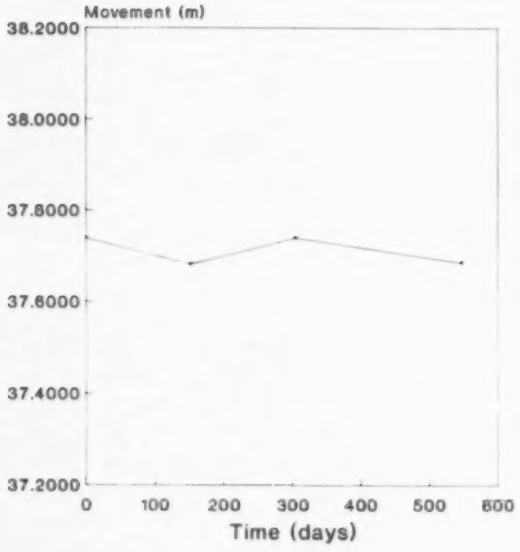
Subsidence Levels
Station E3



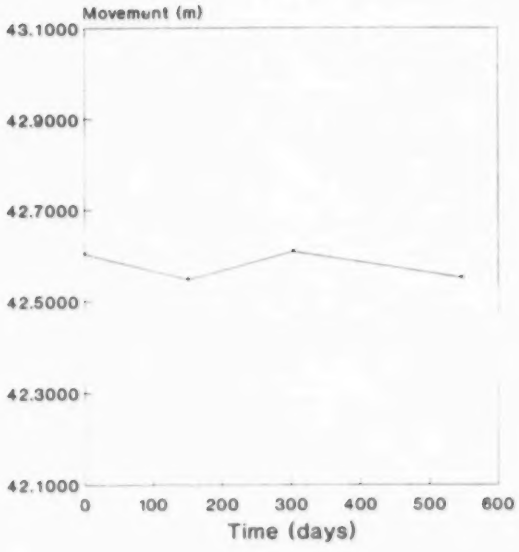
Subsidence Levels
Station E4



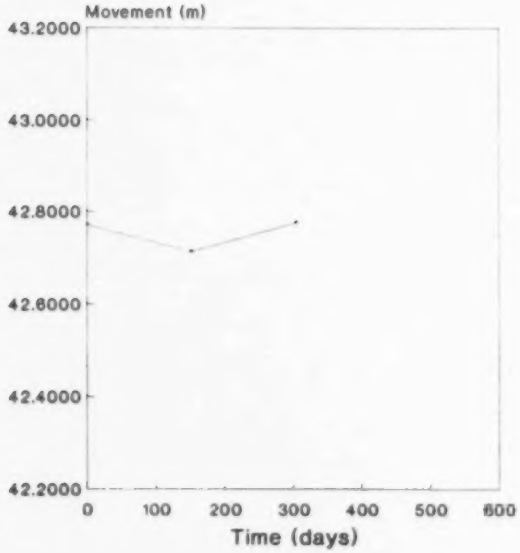
Subsidence Levels
Station E5



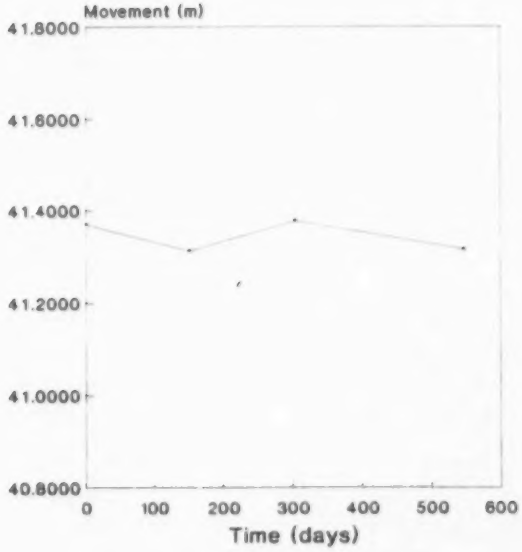
Subsidence Levels
Station E6



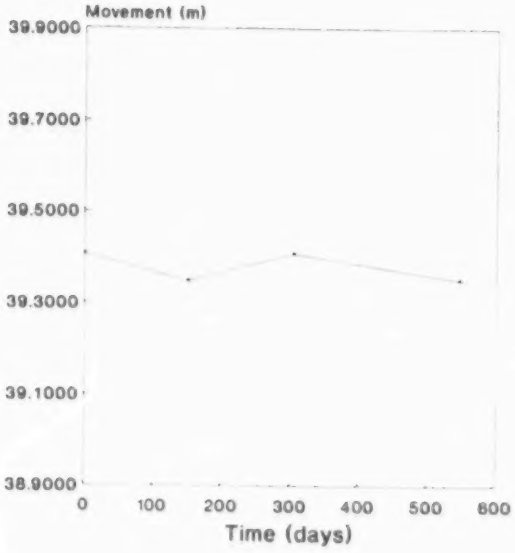
Subsidence Levels
Station E7



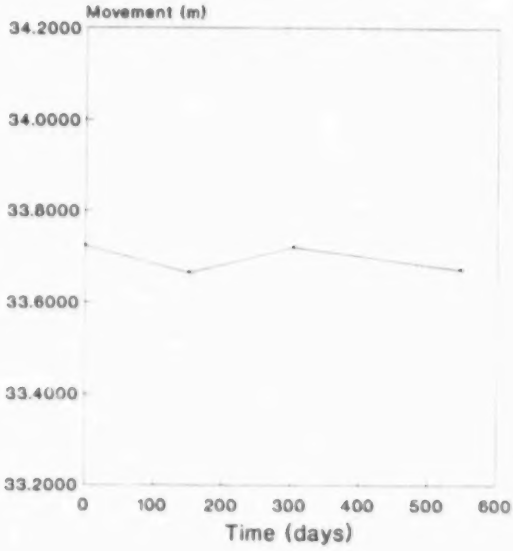
Subsidence Levels
Station E8



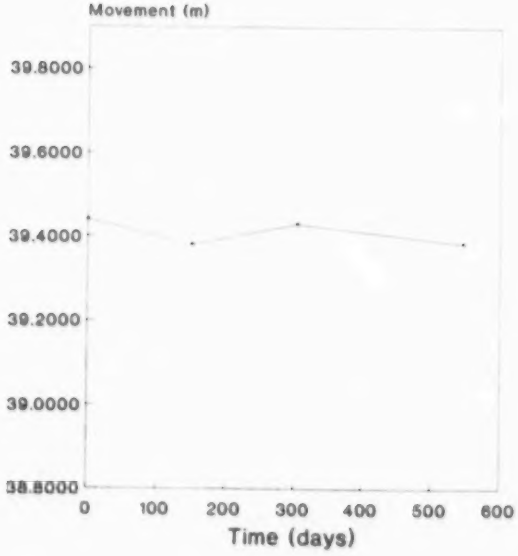
Subsidence Levels
Station E9



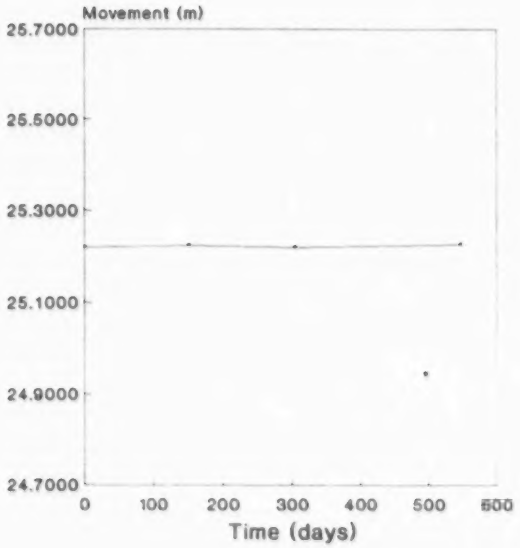
Subsidence Levels
Station E10



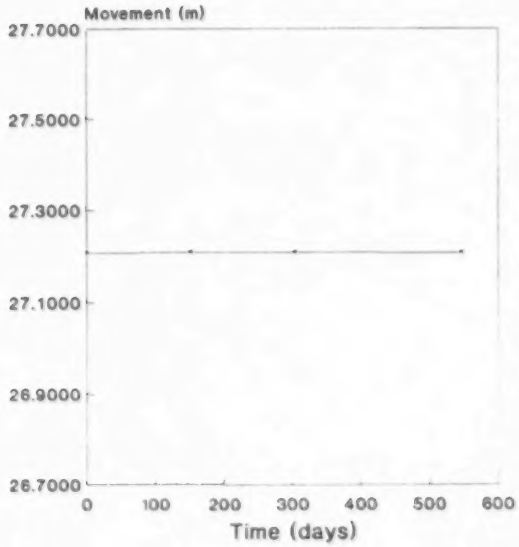
Subsidence Levels
Station E11



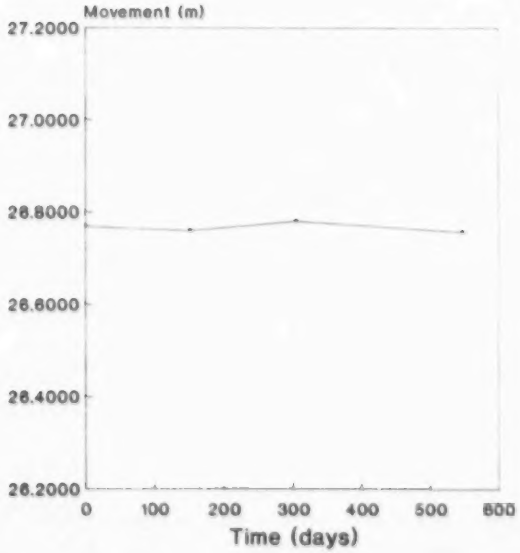
Subsidence Levels
Station ML2



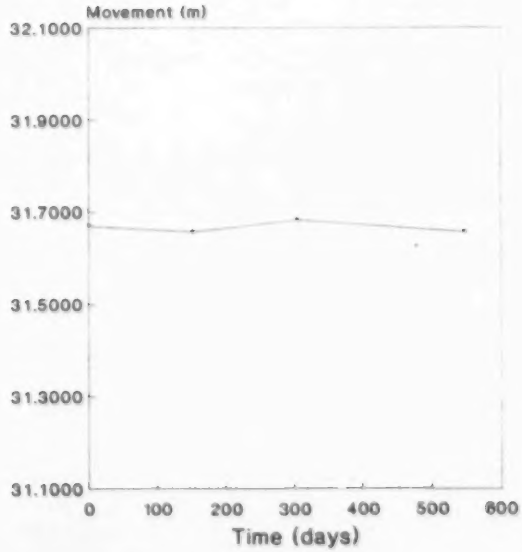
Subsidence Levels
Station ML3



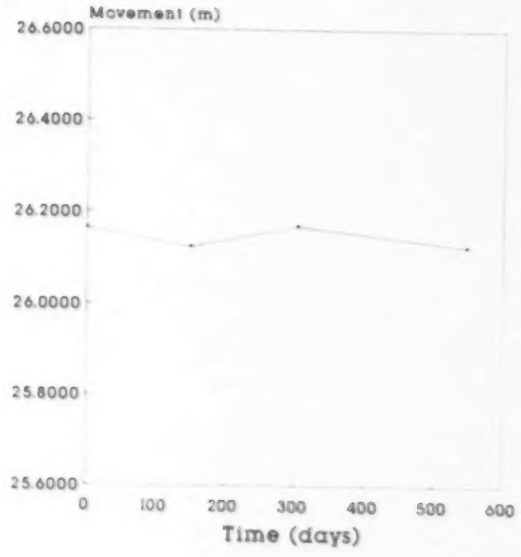
Subsidence Levels
Station ML4



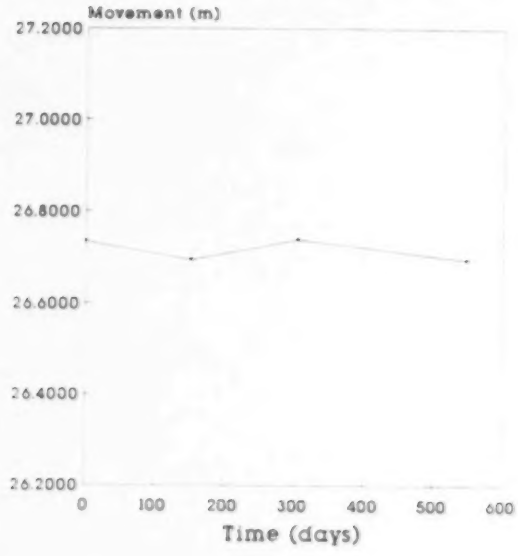
Subsidence Levels
Station ML5



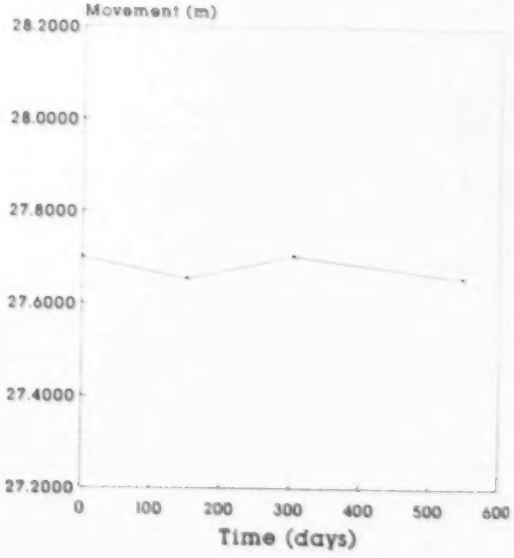
Subsidence Levels
Station ML7



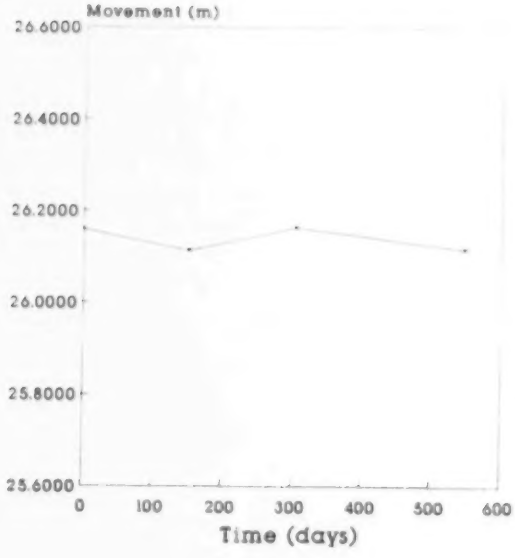
Subsidence Levels
Station ML8



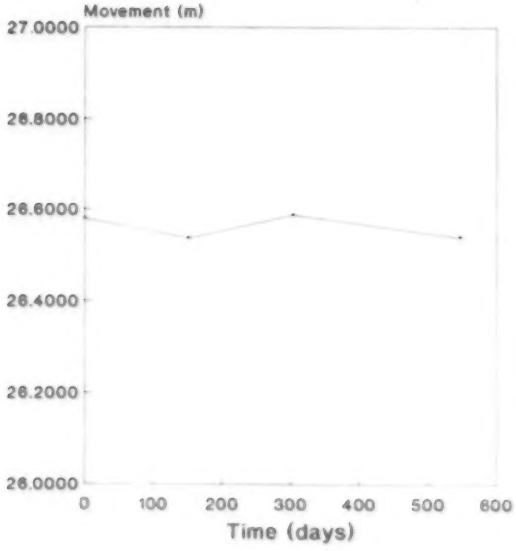
Subsidence Levels
Station ML10



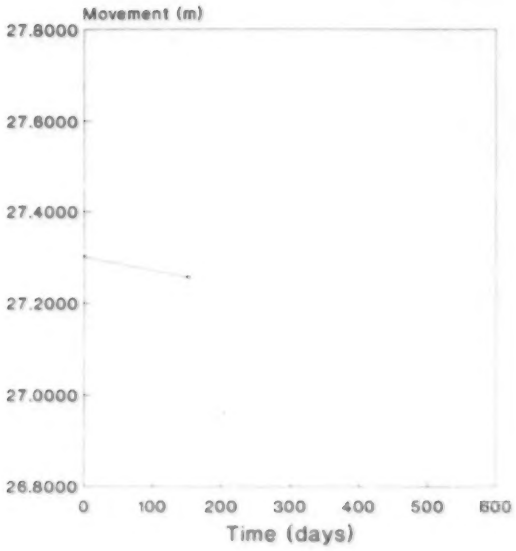
Subsidence Levels
Station ML11



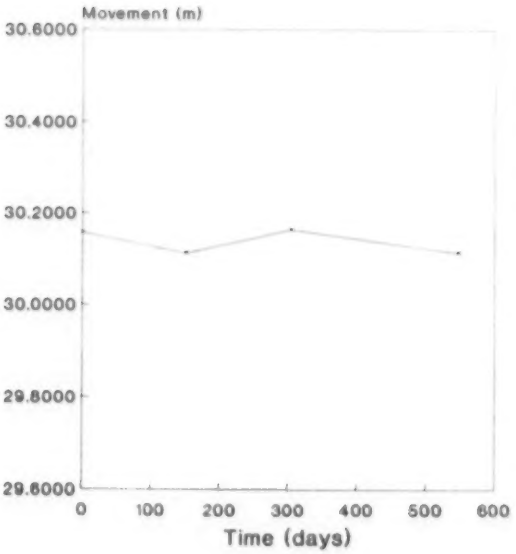
Subsidence Levels
Station ML12



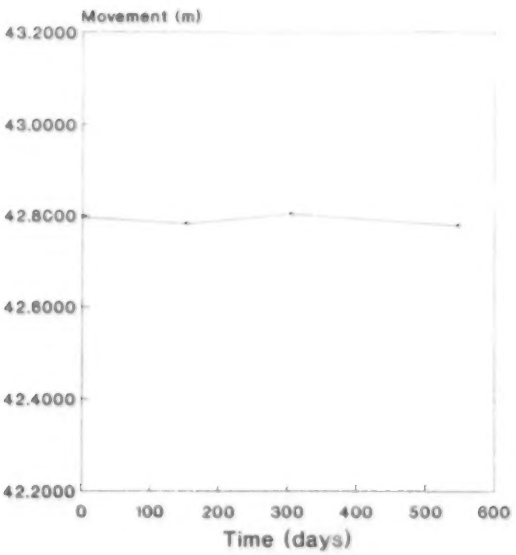
Subsidence Levels
Station ML16



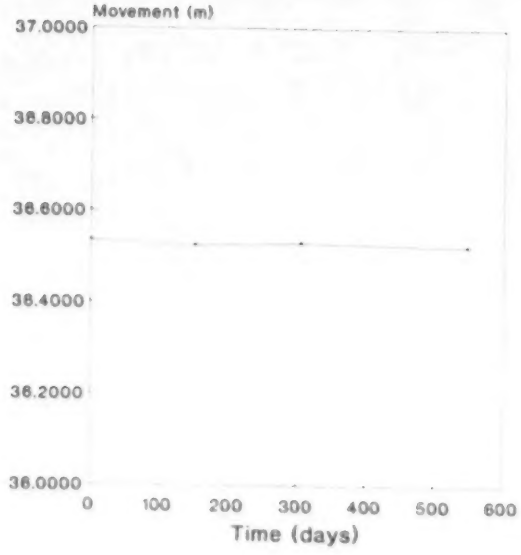
Subsidence Levels
Station ML17



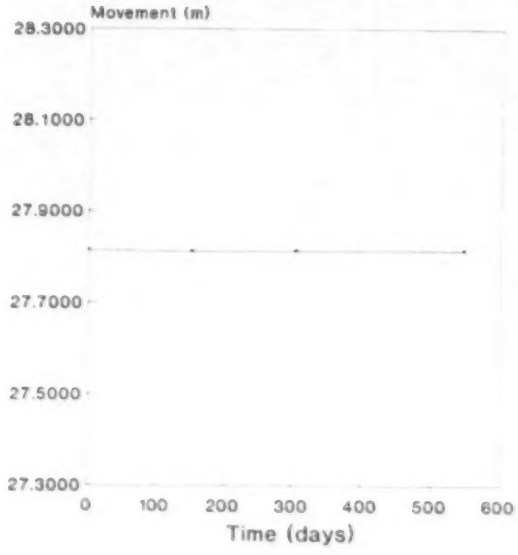
Subsidence Levels
Station ML 18



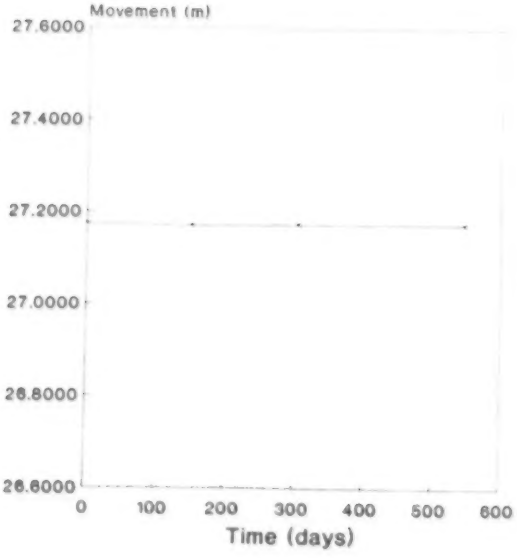
Subsidence Levels
Station ML 19



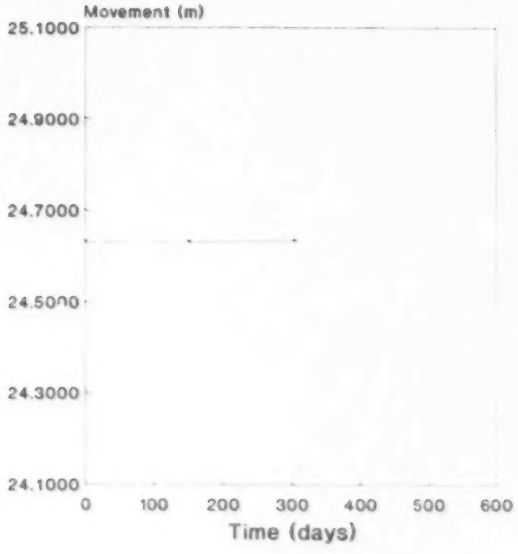
Subsidence Levels
Station ML20



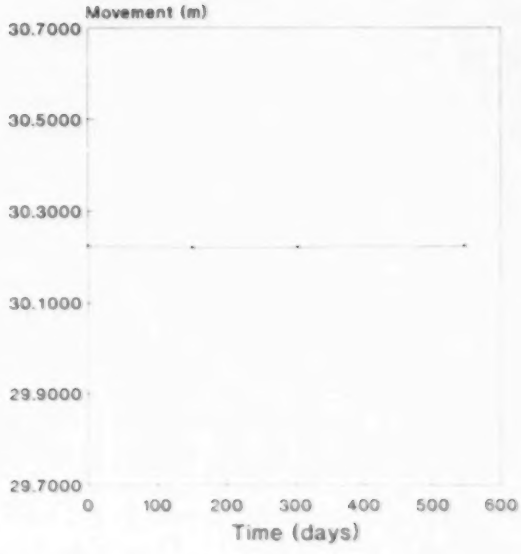
Subsidence Levels
Station ML21



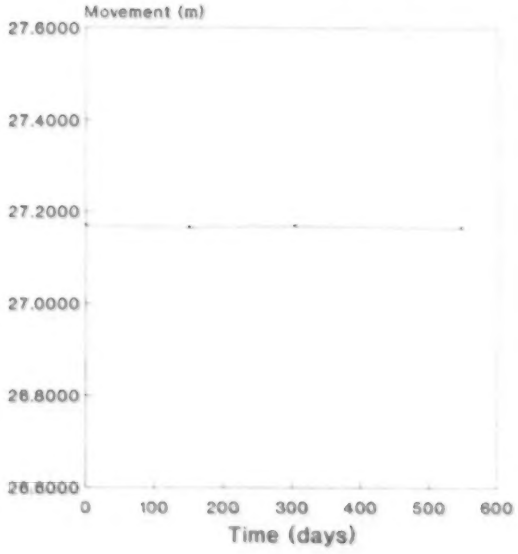
Subsidence Levels
Station PCA 7



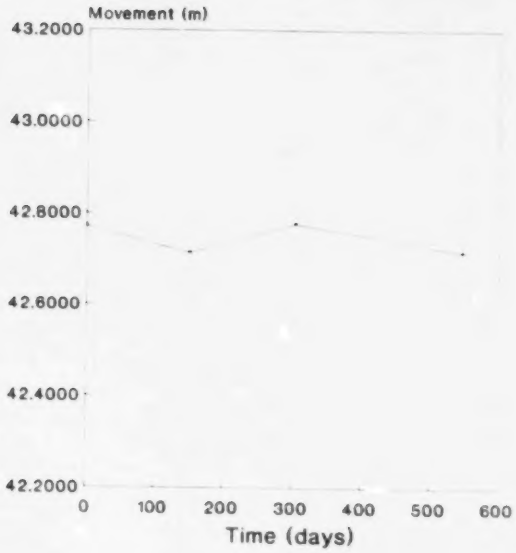
Subsidence Levels
Station PCA 8



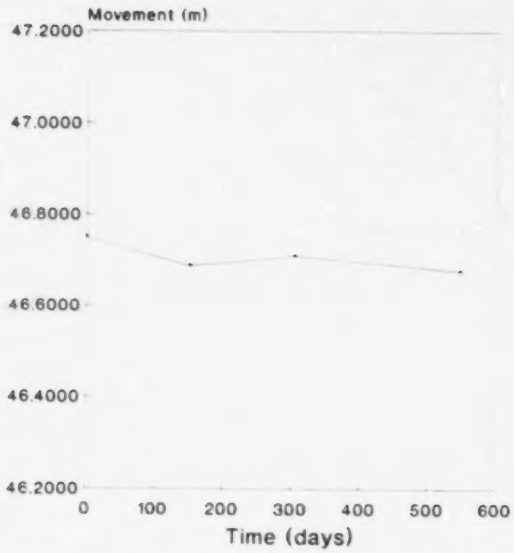
Subsidence Levels
Station PCA 9



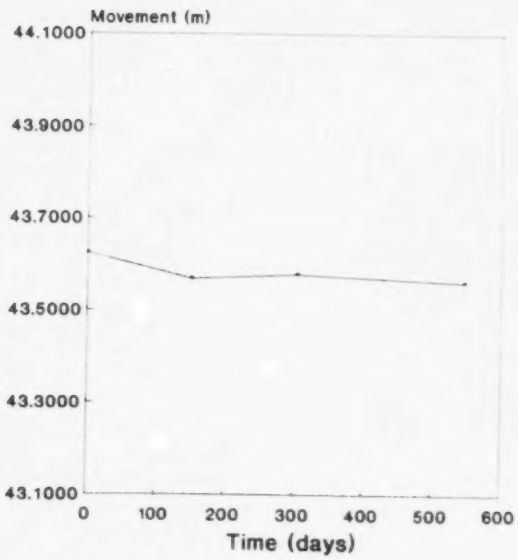
Subsidence Levels
LRIS 9635



Subsidence Levels
LRIS 9637



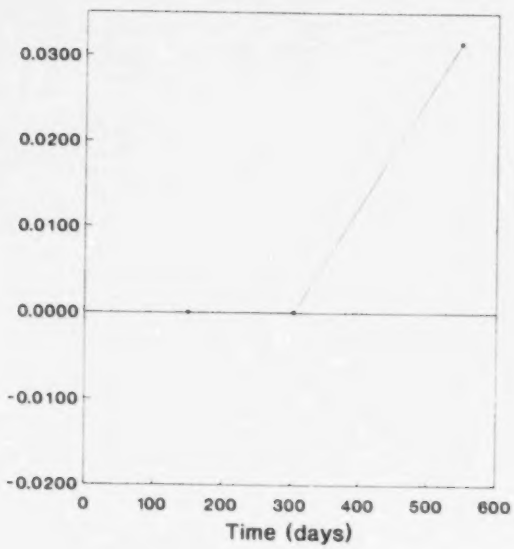
Subsidence Levels
LRIS 9638



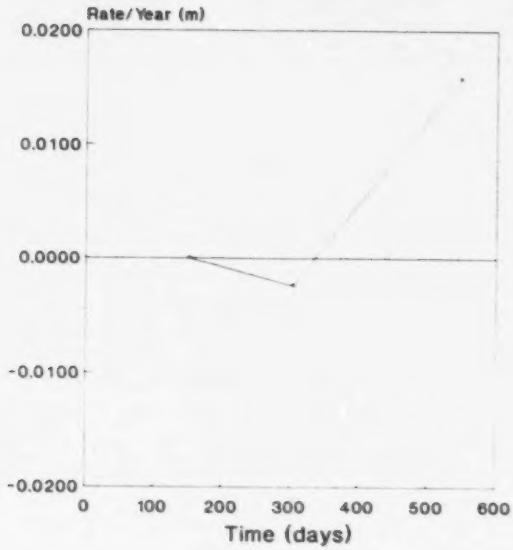
APPENDIX G

GRAPHS SHOWING RATE OF MOVEMENT AT EACH SUBSIDENCE MONITORING STATION

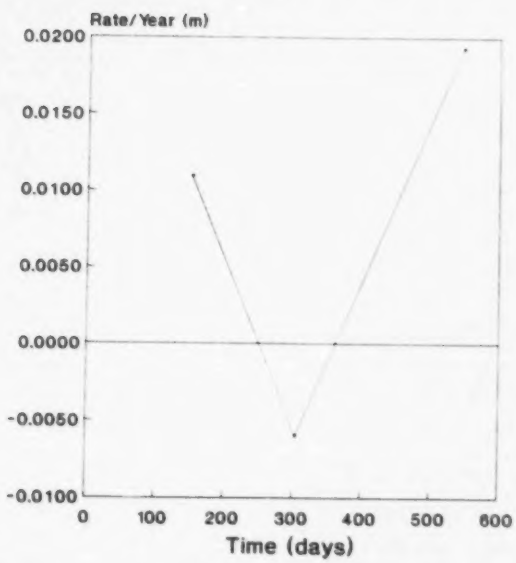
Subsidence Levels
Station 1A



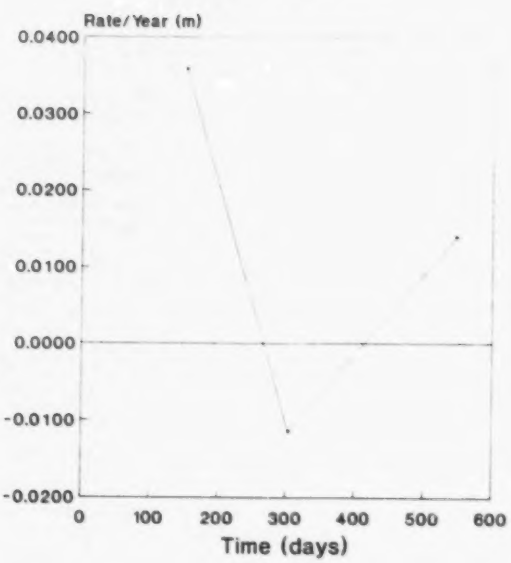
Subsidence Levels
Station 2A



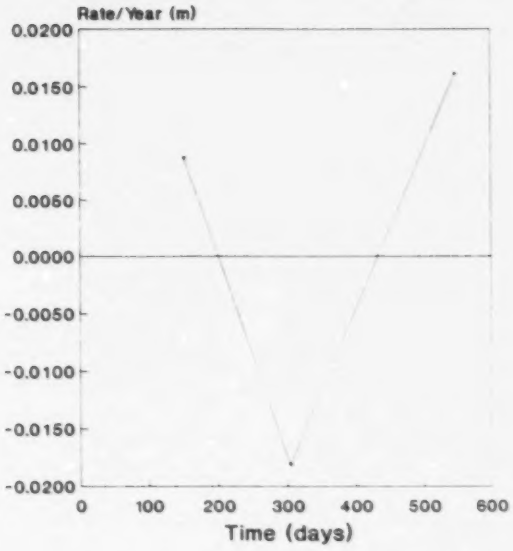
Subsidence Levels
Station 3A



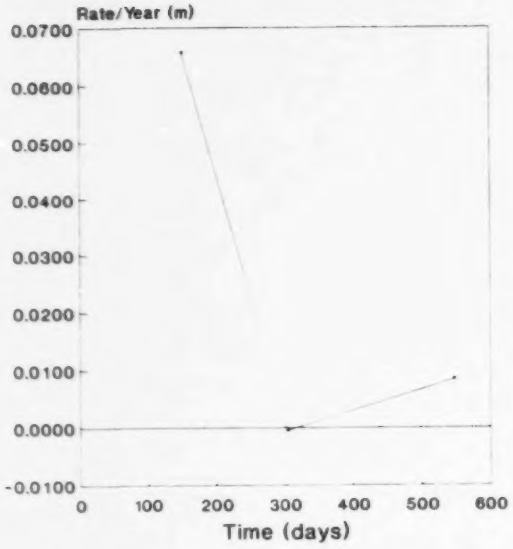
Subsidence Levels
Station 4A



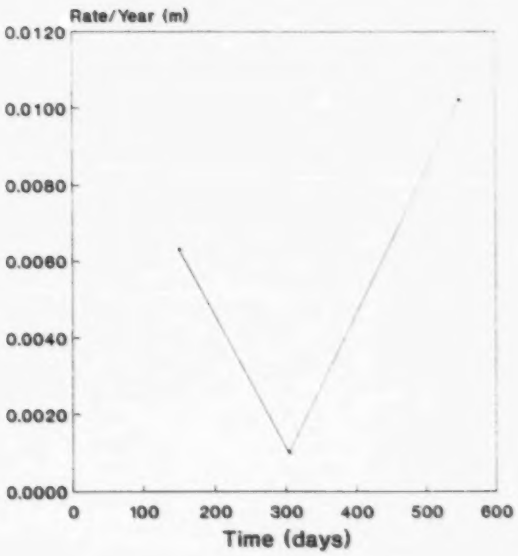
Subsidence Levels
Station 5A



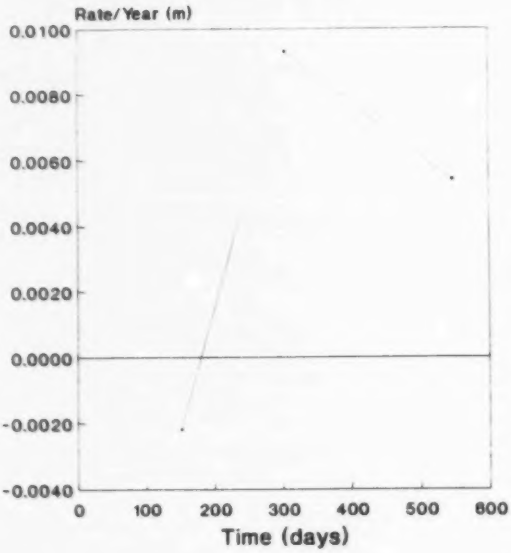
Subsidence Levels
Station 6A



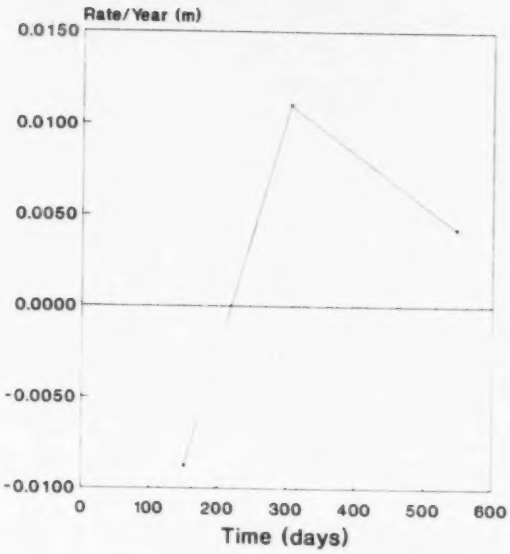
Subsidence Levels
Station 7A



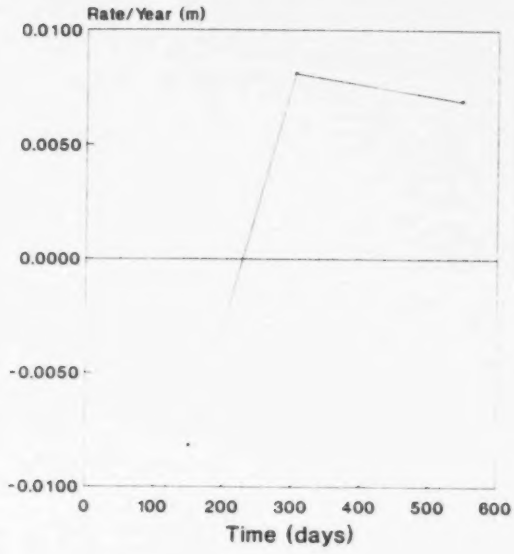
Subsidence Levels
Station 8A



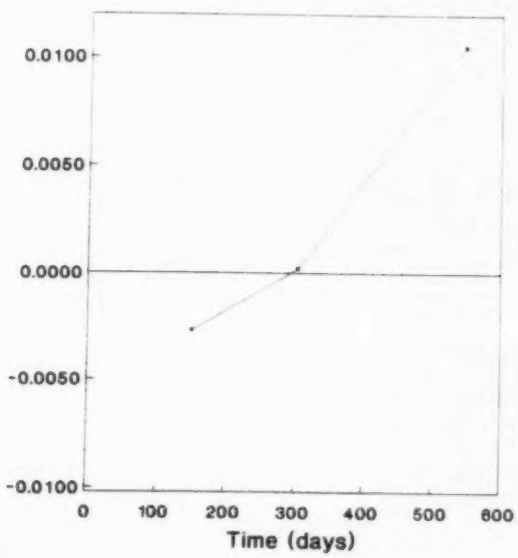
Subsidence Levels
Station 9A



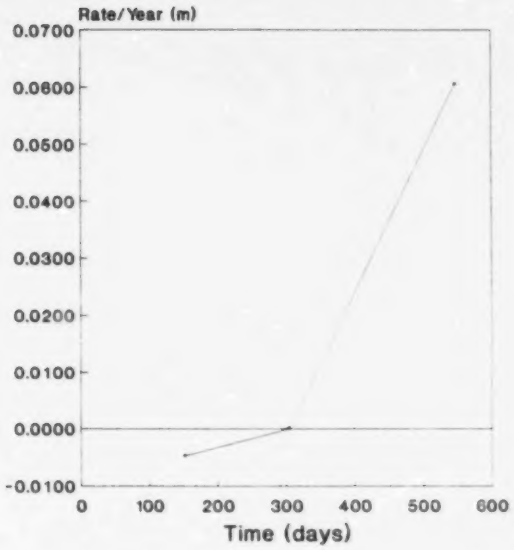
Subsidence Levels
Station 10A



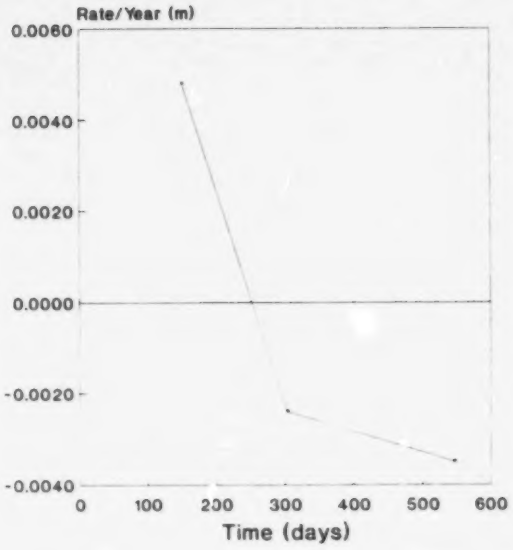
Subsidence Levels
Station 11A



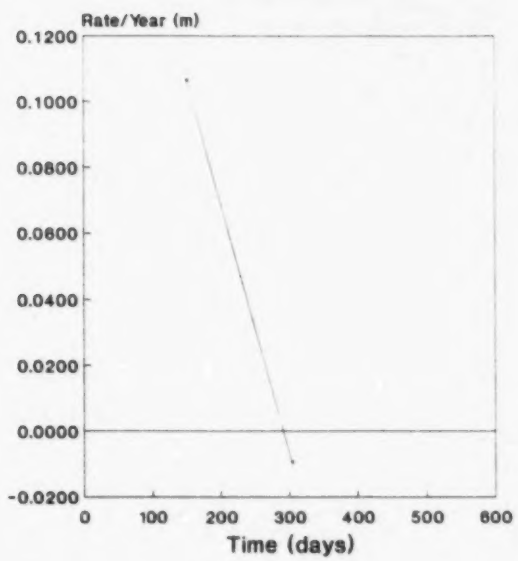
Subsidence Levels
Station B1



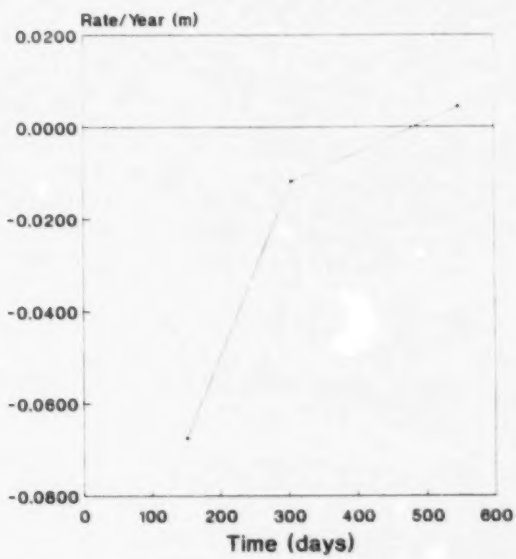
Subsidence Levels
Station B2



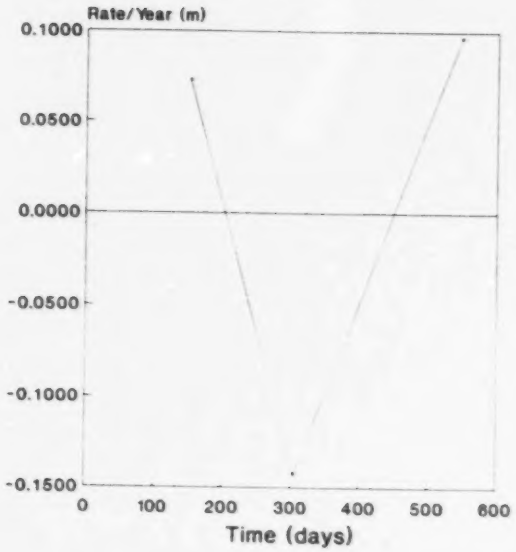
Subsidence Levels
Station B3



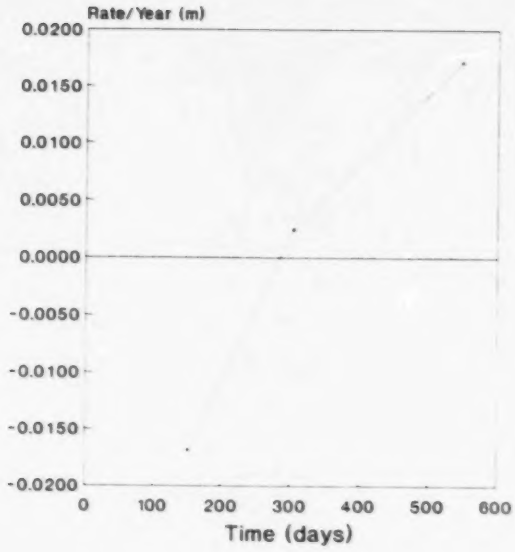
Subsidence Levels
Station B4



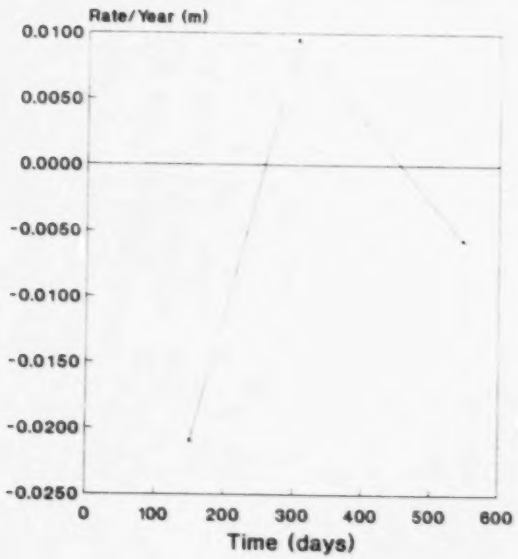
Subsidence Levels
Station B5



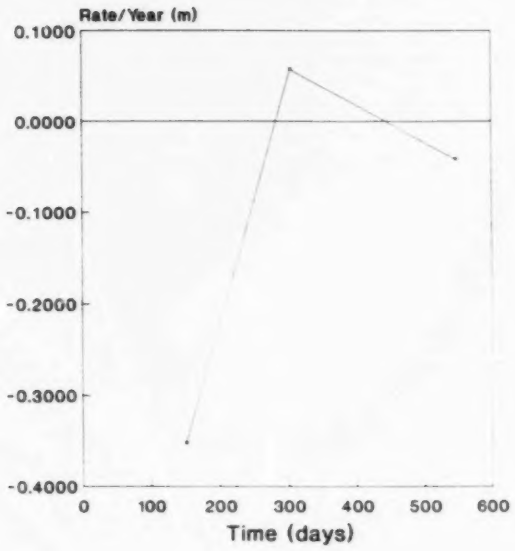
Subsidence Levels
Station B6



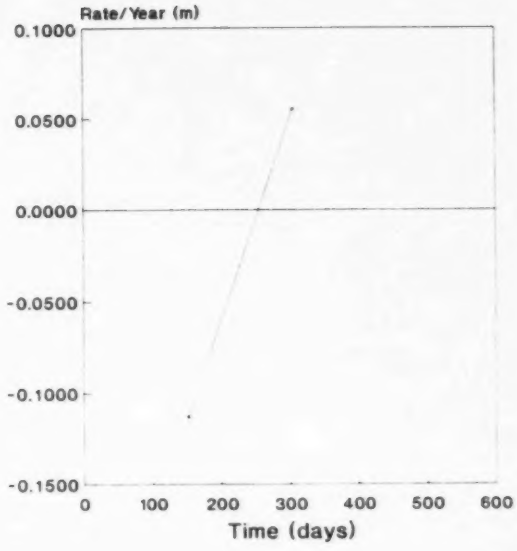
Subsidence Levels
Station B7



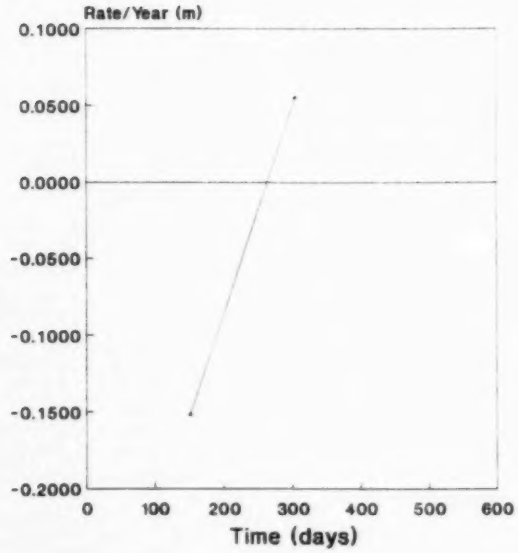
Subsidence Levels
Station C1



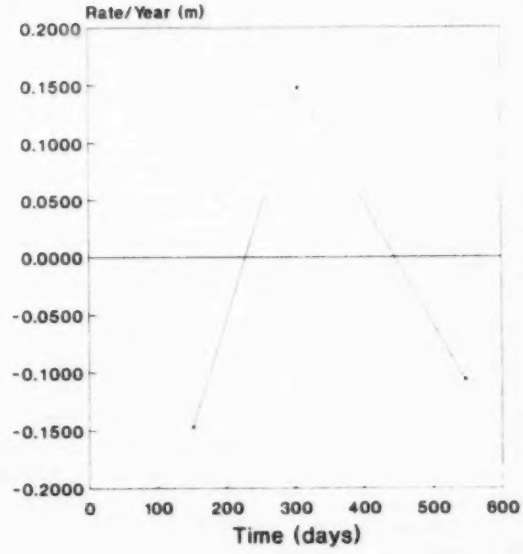
Subsidence Levels
Station C2



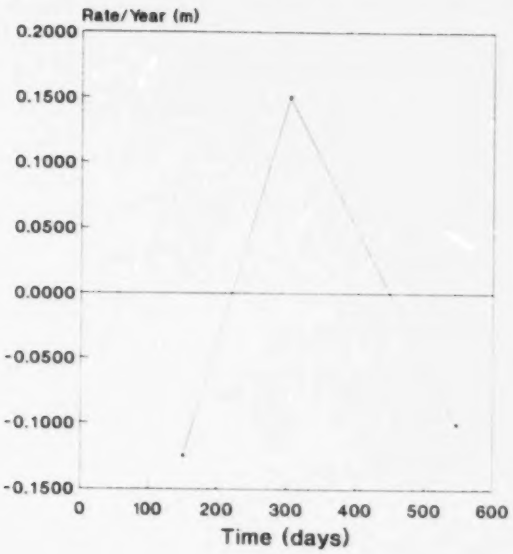
Subsidence Levels
Station C3



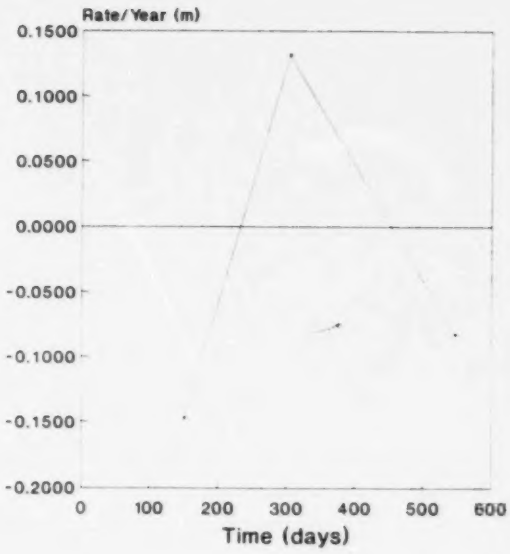
Subsidence Levels
Station C4



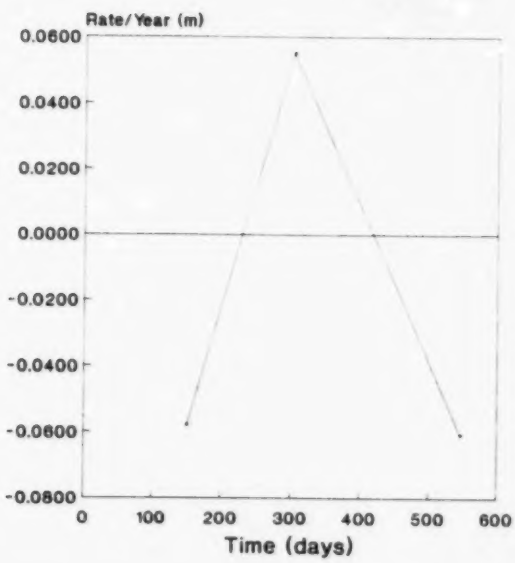
Subsidence Levels
Station C5



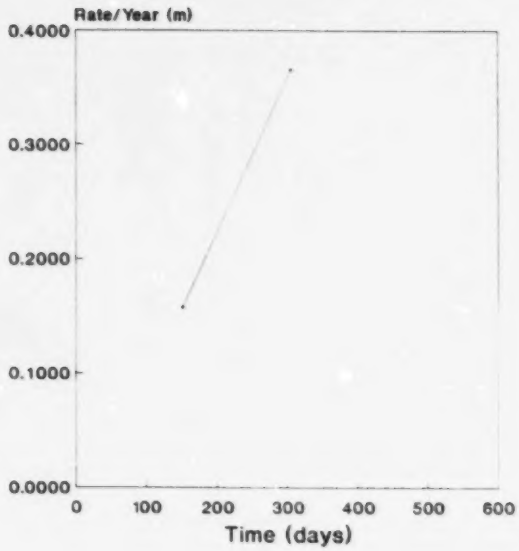
Subsidence Levels
Station C6



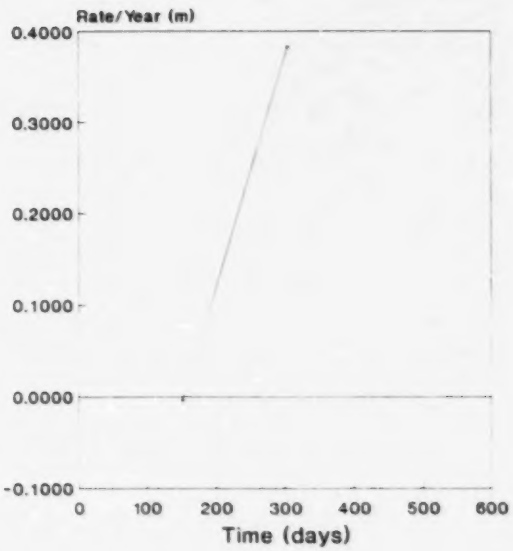
Subsidence Levels
Station C7



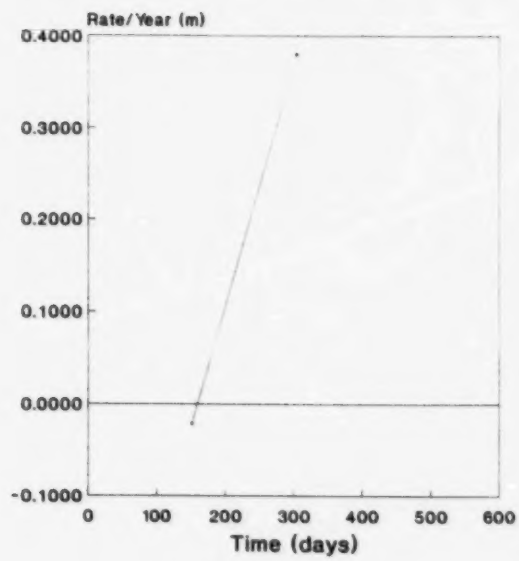
Subsidence Levels
Station D1



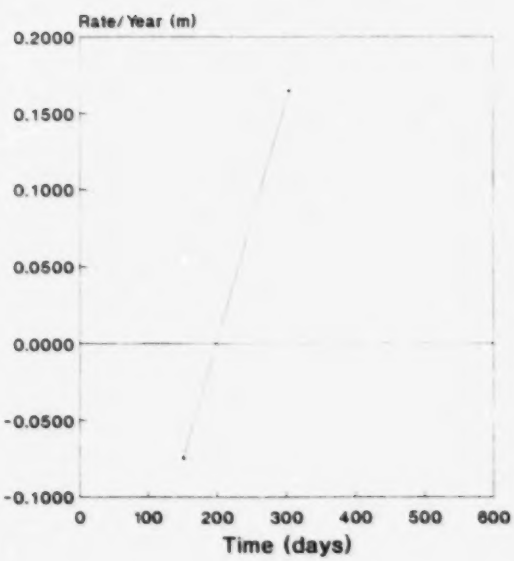
Subsidence Levels
Station D2



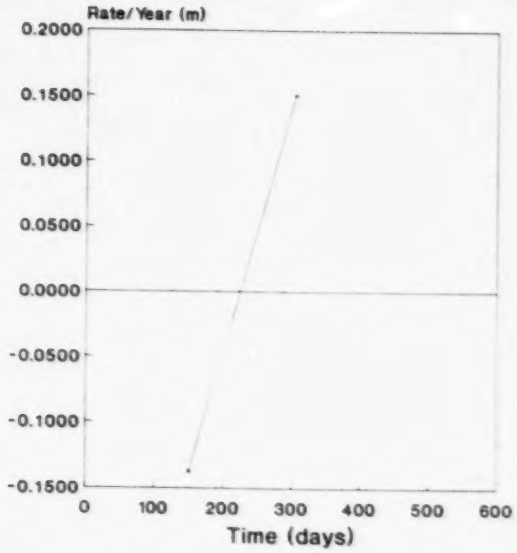
Subsidence Levels
Station D3



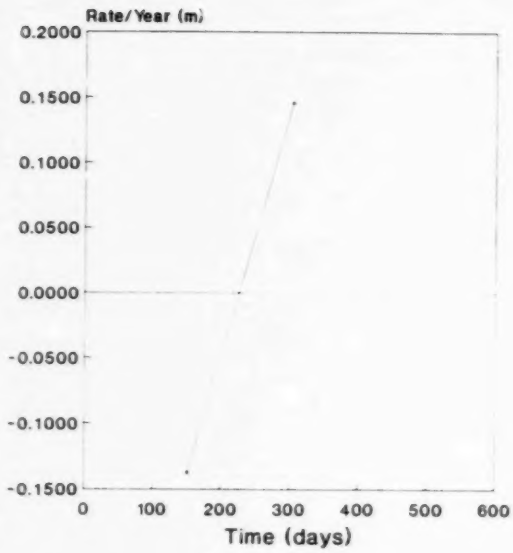
Subsidence Levels
Station D4



Subsidence Levels
Station D5



Subsidence Levels
Station D6



Subsidence Levels
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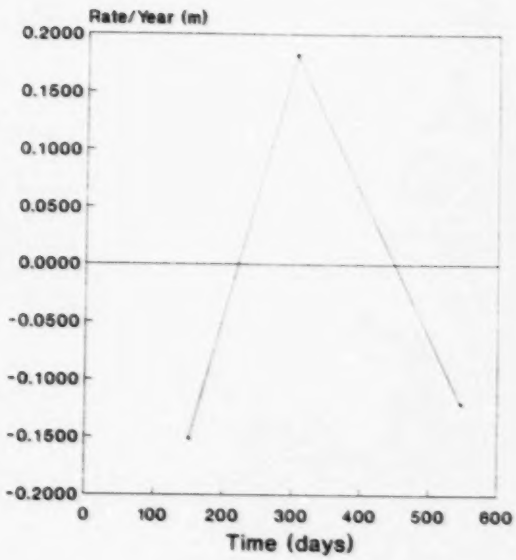

Subsidence Levels
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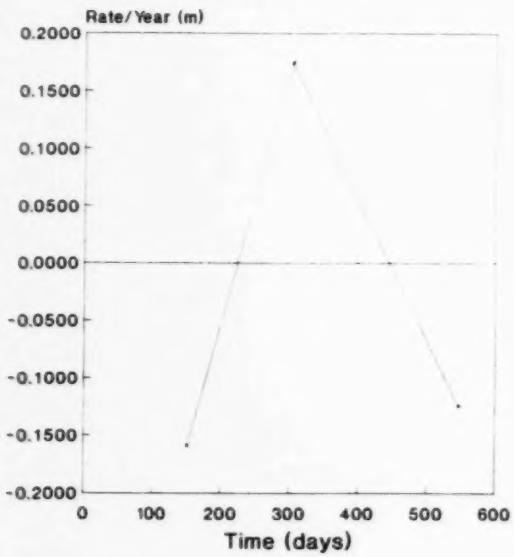
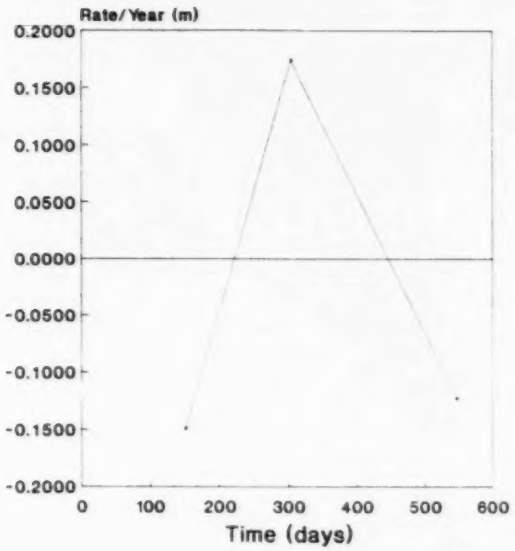
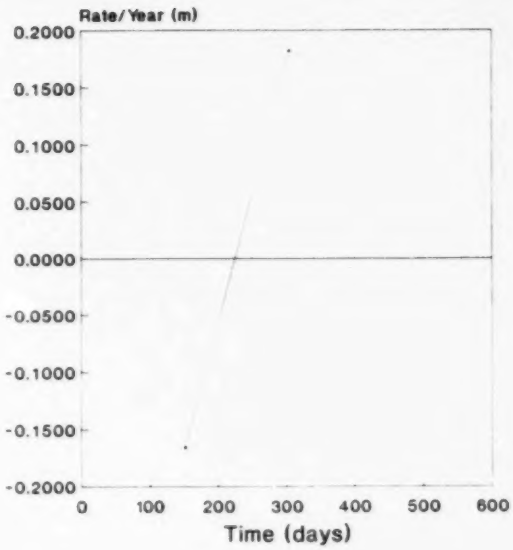


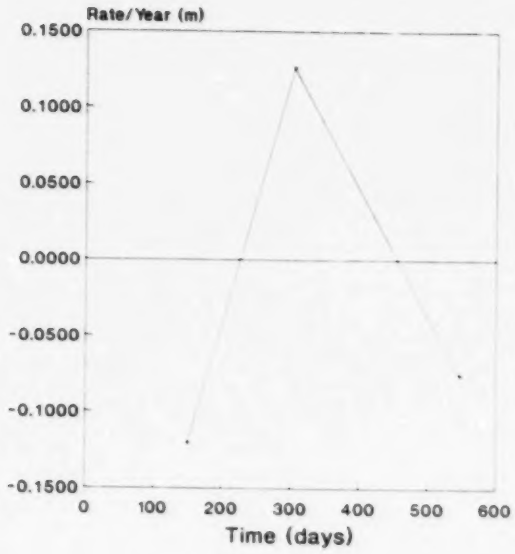
Subsidence Levels
Station D9



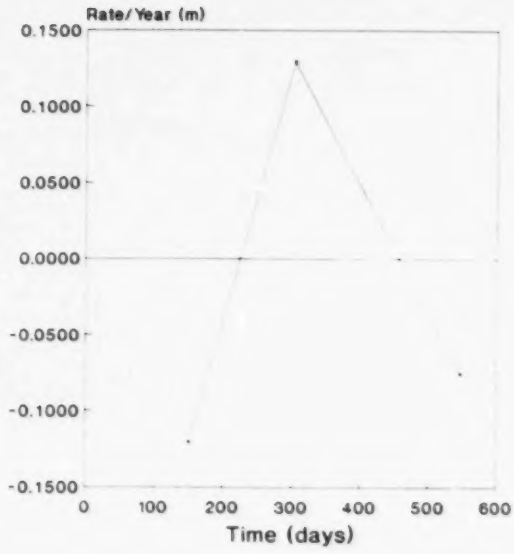
Subsidence Levels
Station D10



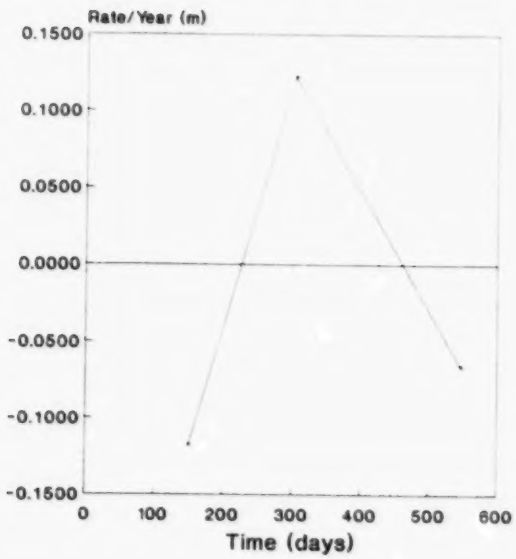
Subsidence Levels
Station E1



Subsidence Levels
Station E2



Subsidence Levels
Station E3



Subsidence Levels
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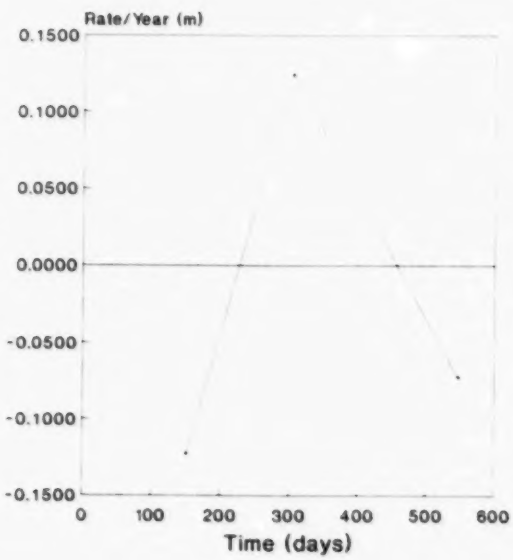
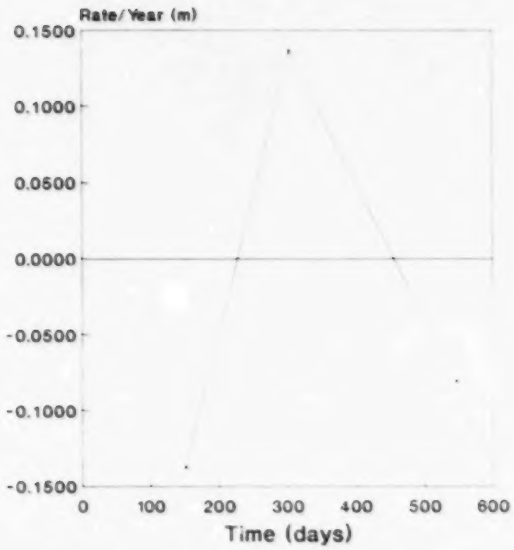
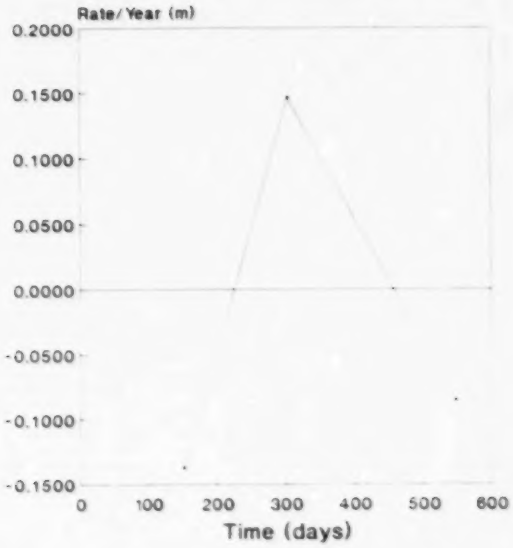


Subsidence Levels
Station E5



Subsidence Levels
Station E6



Subsidence Levels
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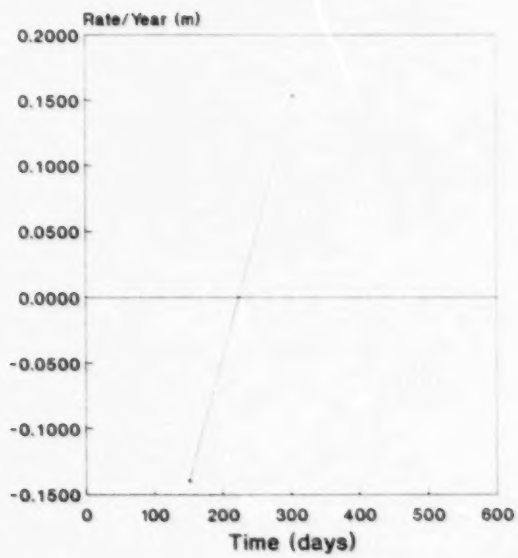

Subsidence Levels
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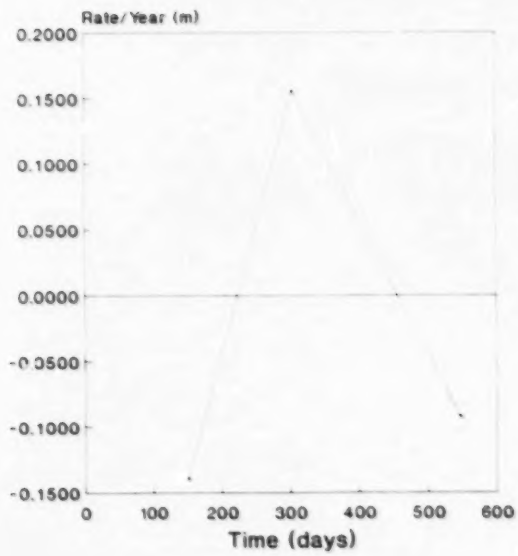
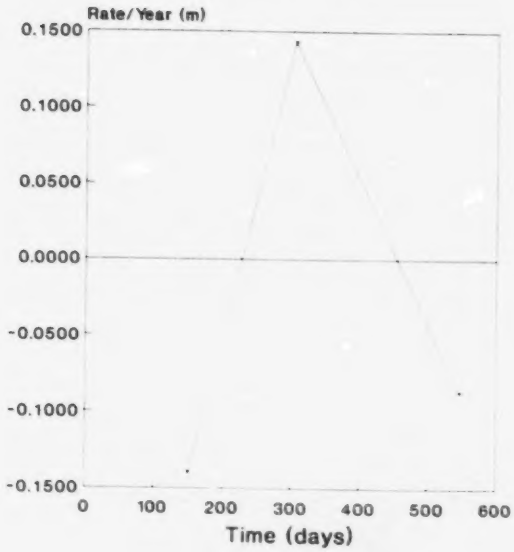


Subsidence Levels
Station E9



Subsidence Levels
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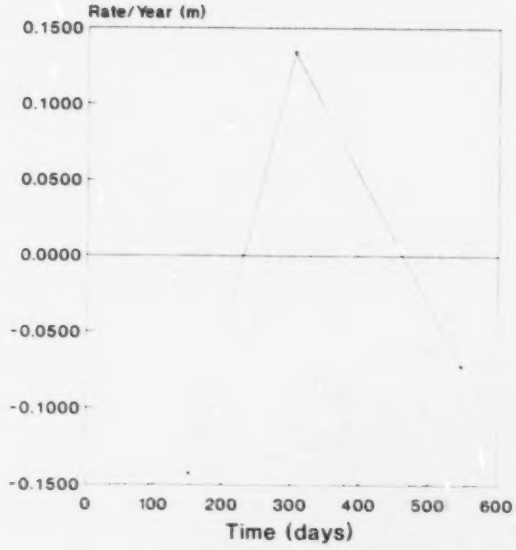
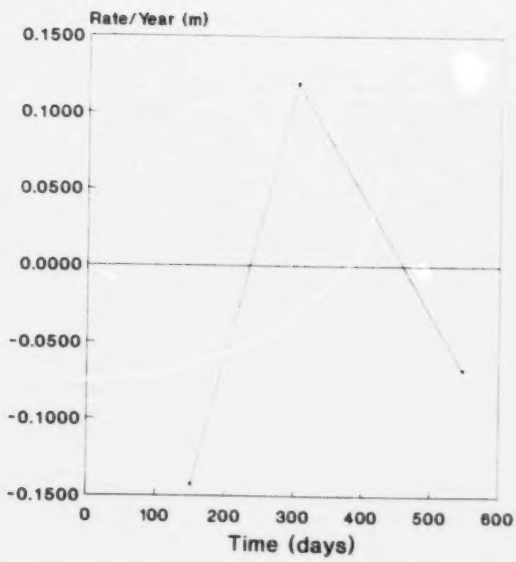
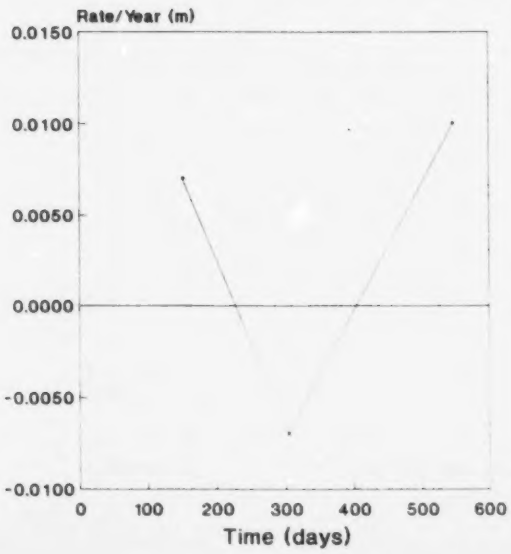


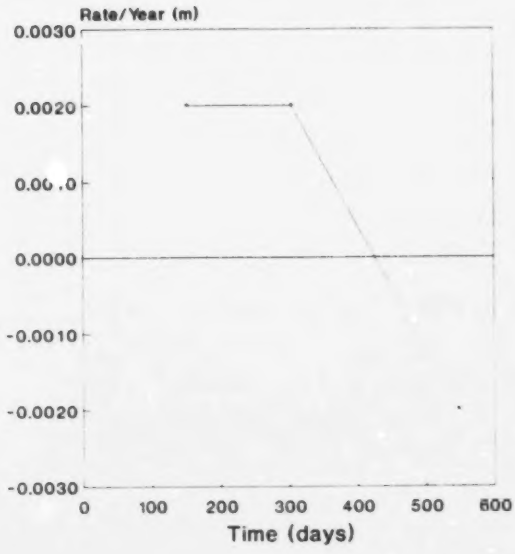
Subsidence Levels
Station E11



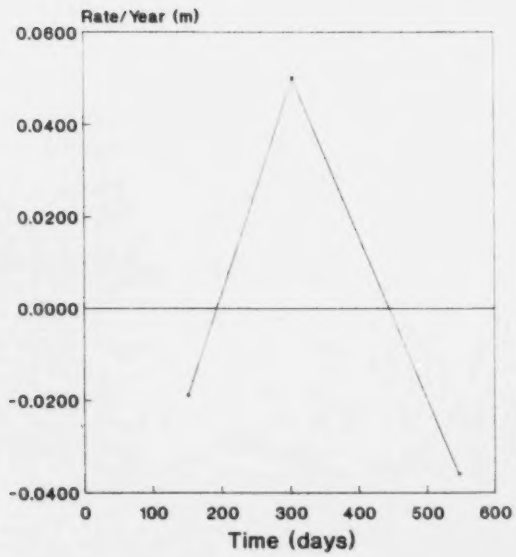
Subsidence Levels
Station ML 2



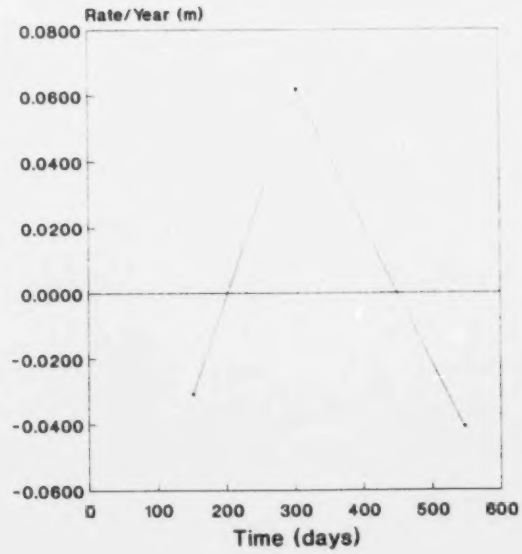
Subsidence Levels
Station ML 3



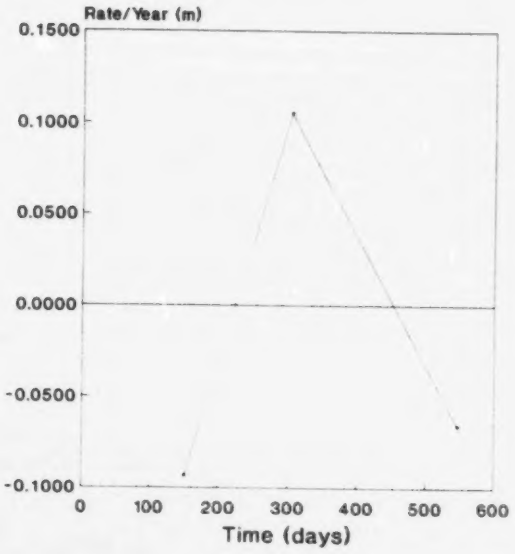
Subsidence Levels
Station ML 4



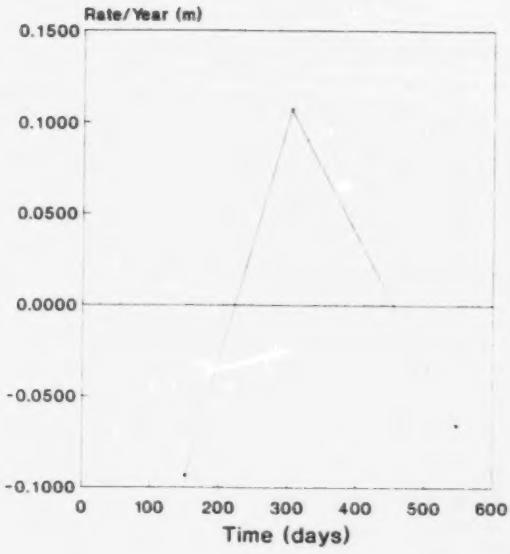
Subsidence Levels
Station ML 5



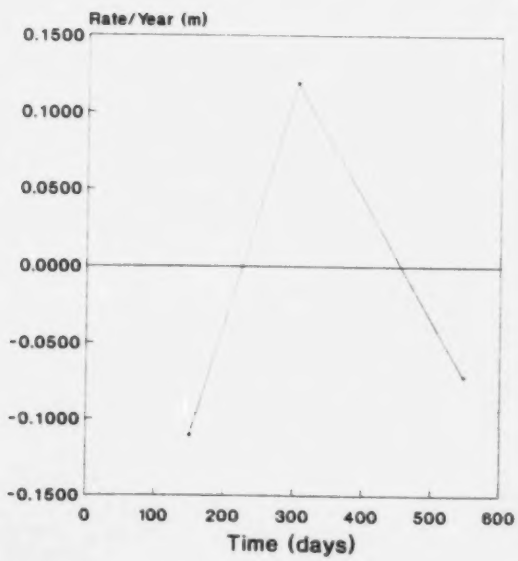
Subsidence Levels
Station ML 7



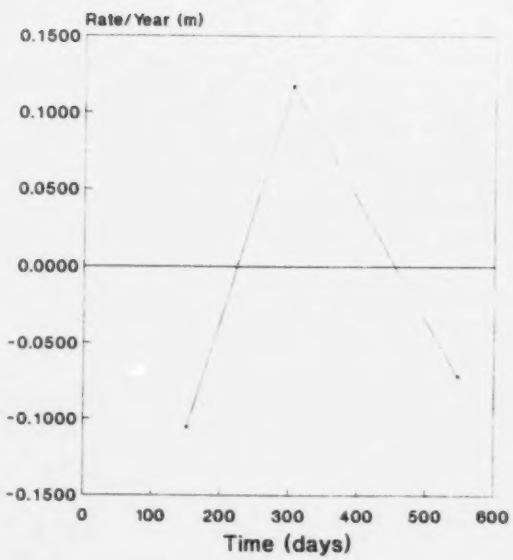
Subsidence Levels
Station ML 8



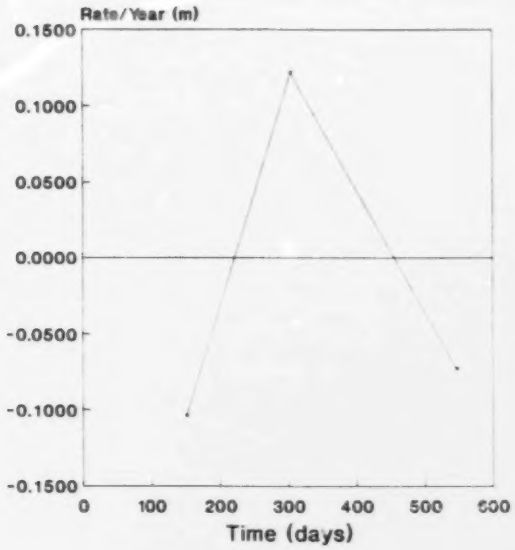
Subsidence Levels
Station ML 10



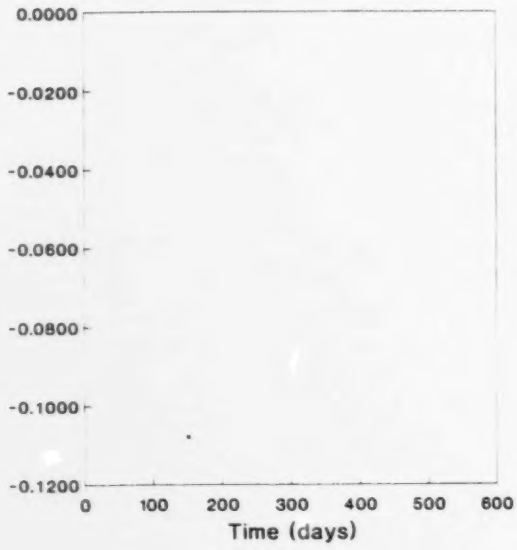
Subsidence Levels
Station ML 11



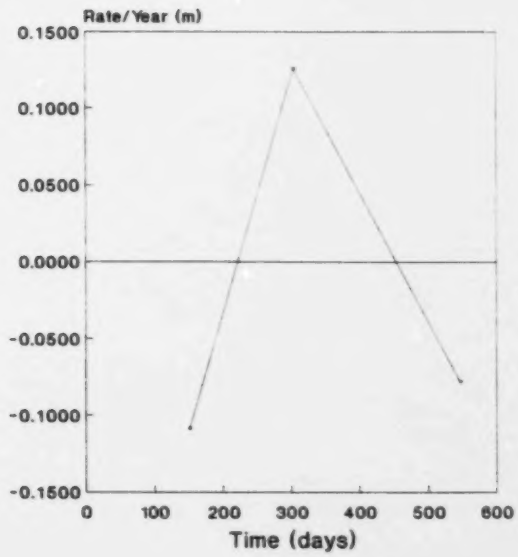
Subsidence Levels
Station ML 12



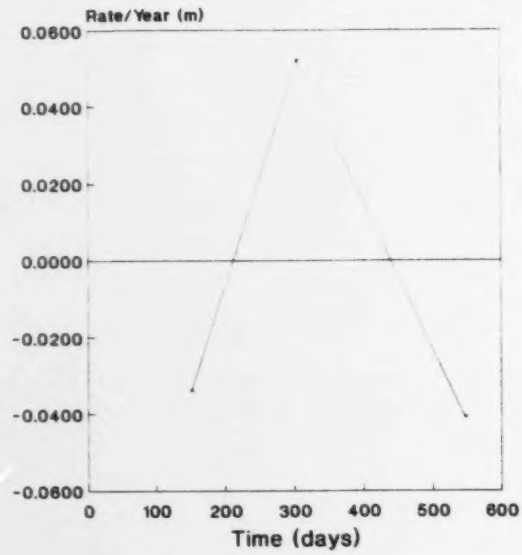
Subsidence Levels
Station ML 16



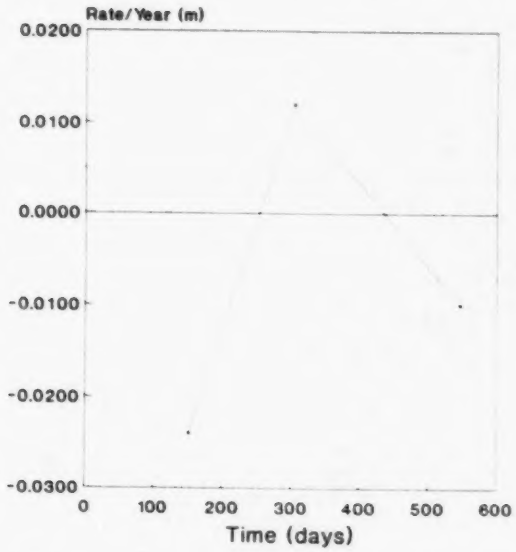
Subsidence Levels
Station ML 17



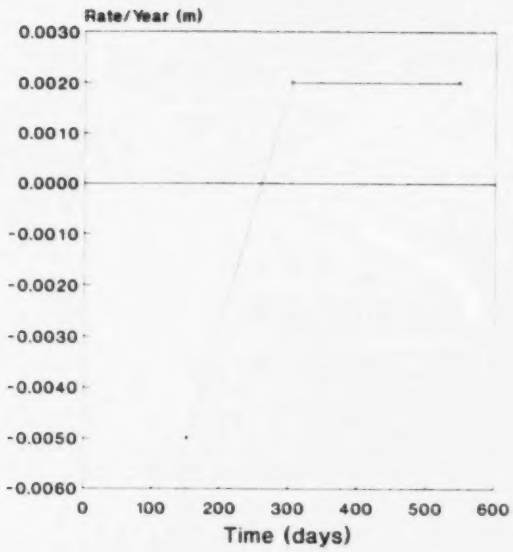
Subsidence Levels
Station ML 18



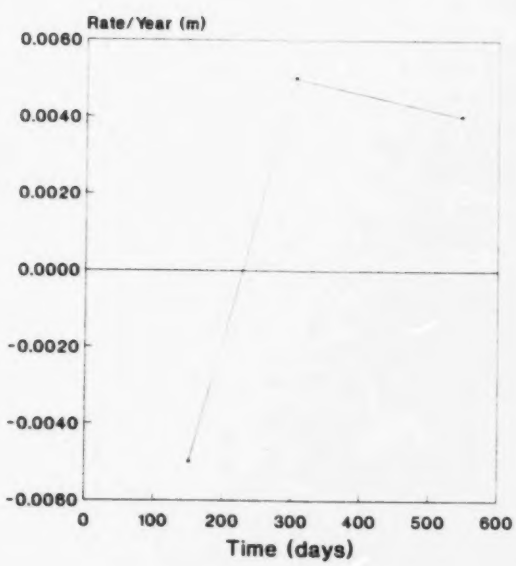
Subsidence Levels
Station ML 19



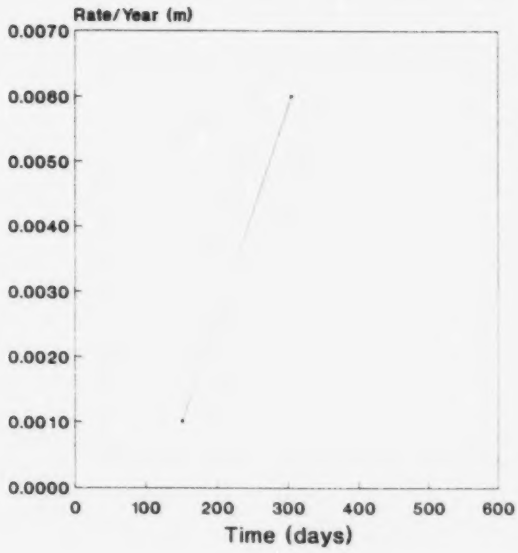
Subsidence Levels
Station ML 20



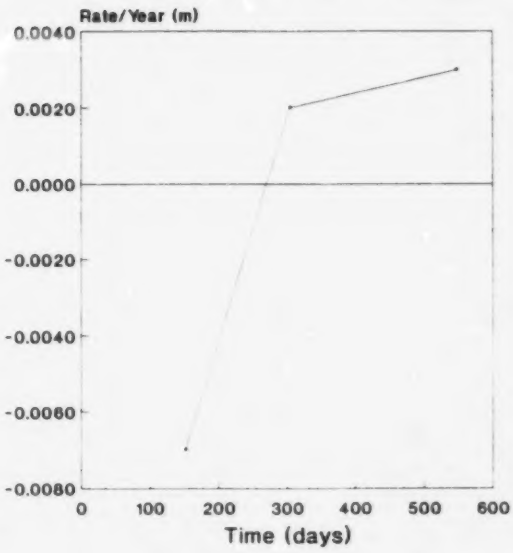
Subsidence Levels
Station ML 21



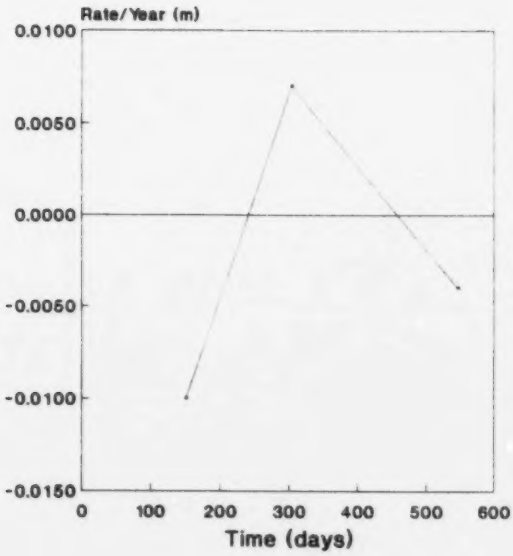
Subsidence Levels
Station PCA 7



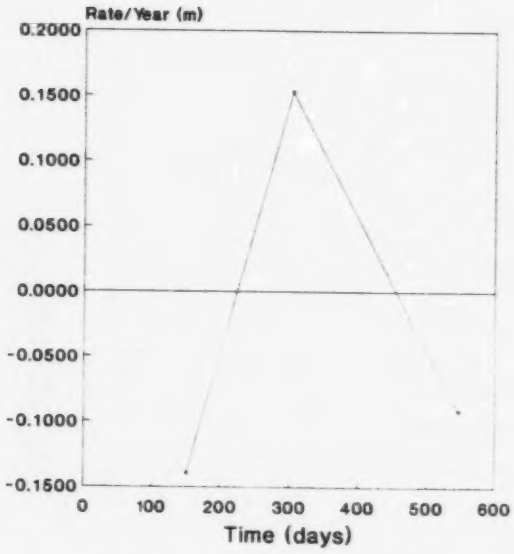
Subsidence Levels
Station PCA 8



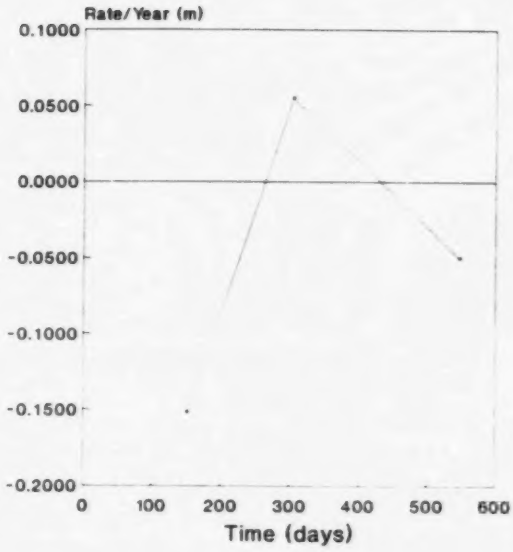
Subsidence Levels
Station PCA 9



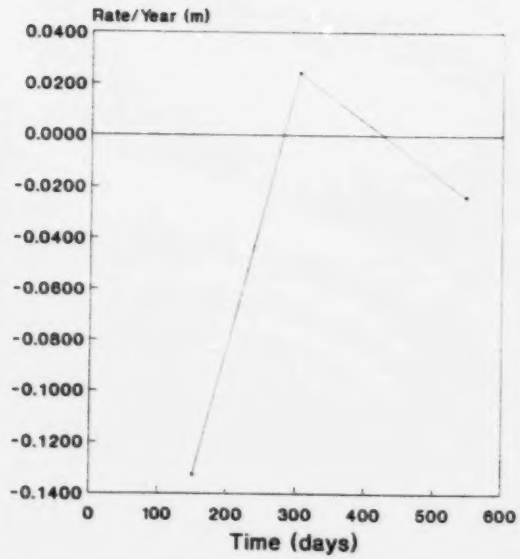
Subsidence Levels
LRIS 9635



Subsidence Levels
LRIS 9637



Subsidence Levels
LRIS 9638



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KENNEBECASIS RIVER

TRANS CANADA HIGHWAY

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735000
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CANADIAN NATIONAL RAILWAY
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FIGURE

PLAN SHOWING PHYS
OF KENNEBECASIS VALLEY R

FIGURE 1

NG PHYSICAL FEATURES
ALLEY RELATIVE TO MINING AREA

735000

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DRN BY: J.CURTIS	POTASH COMPANY OF AMERICA SUSSEX , NEW BRUNSWICK	UPDATE REVISIONS DATE / REV. / INT.
CHKD BY:		
DATE: JULY, 1990		
SCALE: 1 : 10,000	PLAN SHOWING PHYSICAL FEATURES OF	
PLATE NO.		

735000

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CANADIAN NATIONAL RAILWAY

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FIGURE 1

PLAN SHOWING PHYSI
OF KENNEBECASIS VALLEY RE

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FIGURE 1

NG PHYSICAL FEATURES
ALLEY RELATIVE TO MINING AREA

DRN BY: J.CURTIS	POTASH COMPANY OF AMERICA SUSSEX , NEW BRUNSWICK	UPDATE REVISIONS	
CHKD BY:		DATE	REV. INT.
DATE: JULY, 1990	PLAN SHOWING PHYSICAL FEATURES OF KENNEBECASIS VALLEY RELATIVE TO MINE WORKINGS		
SCALE: 1 : 10,000			
PLATE NO.:			
DWG NO.:	(CONTOUR INTERVAL 25m)		